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ZIRCONIUM AND ITS COMPOUNDS WITH A HIGH MELTING POINT

by J. D. FAST.

In this article the preparation of zirconium and its mechanical, chemical and electrical properties are dealt with. The most important applications of zirconium and its compounds with high melting points are then discussed. Zirconium is often used in discharge tubes where its high melting point, small value of secondary emission and, when used as a getter, its property of being able to take up large quantities of oxygen, nitrogen and hydrogen are of significance. Zirconium oxide and zirconium carbide are important as refractory materials.

Introduction

Even since the beginning of the development of the manufacture of electric incandescent lamps, much research has been carried out on metals with high melting points in the laboratories of such factories. The metals in the following groups of the periodic system drew particular attention:

1) The platinum group: platinum, iridium and osmium, the last of which was used for some time as filament in the sources of electric light.
2) The fourth main group: titanium, zirconium, hafnium and thorium.
3) The fifth main group: vanadium, niobium and tantalum, the last of which was used for some time in so-called tantalum lamps.
4) The sixth main group: chromium, molybdenum and tungsten.

At the beginning of the development of the electric incandescent lamp industry (around 1880) practically nothing was known about the mechanical and physical properties of the last three groups mentioned, and very little about their chemical properties. The interest of this industry, however, contributed very much to the research which has led to the fairly extensive knowledge of these metals which we now possess. This interest was at first chiefly directed toward the melting point and the speed of evaporation, but when the electric lamp industry also began to manufacture X-ray tubes, transmitting and receiving valves for radio purposes, rectifier valves etc., it began to include all the properties of the metals under consideration.

The technical result was the present general use of tungsten as filament in incandescent lamps, and the use of this element in the place of all the other substances which were used for that purpose. Several others of the metals mentioned, such as zirconium, tantalum and molybdenum, have also found uses, although less important ones.

The aim of this article is to make several statements about the properties and applications of the element zirconium and several of its compounds. We shall discuss successively the metal, the oxide (ZrO_2) and the carbide (ZrC).

The metal in the pure state is used chiefly in transmitting valves and other discharge tubes, where use is made of its great chemical affinity for various other elements such as oxygen, nitrogen, carbon and hydrogen. The oxide is chiefly used as a refractory and as an opacifier for glazes and enamels. The carbide is still little used, but it shares the interest which has existed during the last ten or fifteen years for the metallic carbides with a very high melting point and very great hardness.

Brittle and ductile zirconium

Twenty-four years ago the first scientific publication from the Philips Laboratory appeared [1]. It contained statements about the preparation of metallic thorium, uranium, zirconium and titanium. Zirconium was prepared by reduction of zirconium tetrachloride ($ZrCl_3$) with sodium. The metal was obtained in the form of a powder and the size of the grain depended upon the reduction temperature, the nature of the chloride, etc. Later the method was improved upon by previously subliming the chloride in hydrogen and thus obtaining it in large compact pieces. If this sublimed chloride is used, and if it is reduced in large portions at a fairly high temperature, the metal is obtained in the form of chunks with dimensions of several centimetres, which are, however, porous. This method of preparation produces metal of great purity and is still one of the best methods of preparing zirconium in the form of a powder or of porous chunks. The best samples were found upon analysis to have a purity of 100 per cent. The separate grains showed a certain ductility (mechanical deformability). It was, however, very remarkable that when a rod was pressed from the pure metal powder, according to the method used in working tungsten, and when this rod was sintered at a high temperature in a very high vacuum, the rod showed practically no sign of ductility. Working to sheet or wire by rolling, hammering and drawing was therefore impossible. Since however chemical analysis indicated a very high degree of purity, as was mentioned above, it was for many years generally assumed that zirconium is a very brittle metal and must be considered to belong to the so-called half-metals.

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[1] D. Lely and L. Hamburger, Herstellung der Elemente Thorium, Uran, Zirkon und Titan, Z. anorg. allg. Chem. **87**, 209, 1914.

However, thirteen years ago an entirely new method of preparing zirconium in the form of rods was discovered in this laboratory ²), namely by thermal decomposition of zirconium tetraiodide on a glowing filament (see below) and the rods as prepared were found to possess a high degree of ductility. The deformability is so great that it is now even possible to cold-work rods of 7 mm thickness to very thin wire and sheet. The crystal structure of ductile zirconium was found to be the same as that of brittle zirconium, so that it was not a question of two allotropic modifications. It has therefore to be assumed that the brittle zirconium contained one or more impurities of which chemical analysis gave no indication.

Only in recent years has it become possible to arrive at a reasonably satisfactory explanation of this phenomenon. It has been found that zirconium is able to take up quantities of oxygen and nitrogen in solid solution. When these elements are present in the dissolved state they have a very detrimental influence on the mechanical properties of metals, so that very small amounts are already enough to make the metal brittle. Titanium which can also contain considerable quantities of oxygen and nitrogen in solid solution, exhibits the same phenomena as zirconium. Thorium, however, which belongs to the same group of the periodic system as titanium and zirconium, is found to have no appreciable dissolving power for oxygen and nitrogen. The result is that this last metal does not exhibit the phenomenon mentioned: thorium rods can also be obtained in the ductile state by compression and sintering of the powder.

We must assume that grains of metal obtained by the reduction of the chlorides of the three metals in question are covered with a film of oxide and (or) nitride. In the sintering of rods pressed from the powders, the oxygen and nitrogen dissolve in the metal in the case of zirconium and titanium, and the metal thus becomes brittle, while in the case of thorium, the oxide and nitride remain present as such in the rod. It is true that in the sintering of pressed thorium rods a change in the structure also appears, but this change in the structure has a favourable influence on the mechanical properties. It consists namely in the fact that the oxide or nitride is collected into separate grains, which are then present after sintering surrounded by a coherent basic mass of ductile metal. This makes it understandable that much greater quantities of oxygen and nitrogen are required to render thorium brittle than in the case of zirconium and titanium.

The grains of zirconium and titanium obtained by reduction usually contain small traces of oxygen and nitrogen already dissolved, so that each individual grain has a ductility considerably lower than that of the absolutely pure metals, but considerably higher than that of the pressed and sintered rods.

Preparation of ductile zirconium in rod form

Ductile zirconium is prepared by thermal decomposition of zirconium tetraiodide. At a temperature of 431°C the vapour pressure of this compound reaches a value of one atmosphere. If the gaseous iodide comes into contact with a surface whose temperature is higher than 1100°C, it decomposes partially into zirconium and iodine. When the process is carried out in practice the decomposition takes place on a thin wire which is heated by the passage of current to a suitable temperature, for instance 1300°C. The reaction takes place in an apparatus made of pyrex glass into which thick tungsten terminals are fused. The required amount of crude

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²) J. H. de Boer und J. D. Fast, Über die Darstellung der reinen Metalle der Titangruppe durch thermische Zersetzung ihrer Jodide. I. Zirkonium, Z. anorg. allg. Chem. **153**, 1, 1926.

zirconium is introduced into this apparatus in the form of porous chunks (obtained by the reduction of zirconium tetrachloride or of sodium zirconium fluoride with sodium) together with a relatively small amount of iodine. The apparatus is then evacuated to a pressure of about 10^{-6}mm. During evacuation the crude zirconium is heated to drive off adsorbed gases, while the iodine is cooled. After outgassing the apparatus is sealed off and heated in an electric oven. At a temperature of about 100°C (depending on the nature of the crude zirconium) the iodine combines with part of the zirconium to give ZrI_4, and the substance evaporates and is decomposed on the wire into zirconium and iodine when the temperature of the wire is sufficiently high. In this way crystals of zirconium begin to grow on the wire.

The vapour pressure of the iodide at 100°C is so small that it may be neglected, so that upon heating the core wire to 1300°C, for instance, no appreciable growth takes place. At an oven temperature of 150°C the vapour pressure is already so high (about 0.001 mm Hg) that zirconium slowly begins to be deposited on the glowing wire. With increasing temperature of the oven the speed of growth increases and reaches a high value at 250°C. The vapour pressure of the tetraiodide then amounts to about 0.5 mm Hg. From about 250°C, however, the ZrI_4 pressure rises only slightly, because of the fact that above this temperature the tetraiodide begins to react with the excess crude zirconium giving the tri-iodide (ZrI_3), which has no appreciable vapour pressure in this temperature range. At still higher temperatures the di-iodide (ZI_2) is also formed, a compound which also has no appreciable vapour pressure at the temperatures attainable in pyrex glass. Above 310°C the tri-iodide decomposes according to the equation

$$2\ ZrI_3 \rightleftarrows ZrI_2 + ZrI_4.$$

while above 430°C the di-iodide decomposes according to the equation :

$$2\ ZrI_2 \rightrightarrows Zr + ZrI_4$$

At higher temperatures therefore the pressure of ZrI_4 is determined by these equilibria.

The result of these phenomena is that the speed of growth does not increase appreciably above 250°C, and that above 350°C it finally begins to decrease again.

Fig. 1 gives a graphic representation of the speed of formation of ductile zirconium as a function of the oven temperature. The temperature is plotted as abscissa, and as ordinate the weight of the zirconium rods which were obtained after a time of growth of 30 hours. In each separate experiment the oven temperature was kept constant during this time of growth. All the apparatus which were used in these experiments were filled with 250 g. of crude zirconium from the same preparation (obtained by reduction of the chloride) and with 12 g. of iodine. The wire temperature was the same, 1300°C, in all the experiments.

For practical uses zirconium is made in rods about 7 mm thick which weigh about 200 gr. The oven temperature is kept at 250° to 350°C during the preparation. A tungsten wire 40 microns thick is often used as core wire. The tungsten content of the zirconium rods then amounts to 0.01 per cent. For applications in which this tungsten content would be detrimental a core wire of zirconium itself is used.

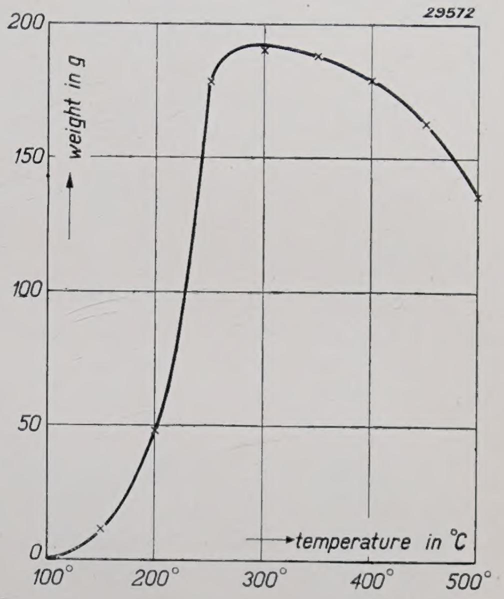

Fig. 1. Speed of formation of zirconium obtained by decomposition of zirconium tetraiodide, as a function of the oven temperature. The weight obtained at the corresponding oven temperature and at a wire temperature of 1300°C after a time of growth of 30 hours is plotted as ordinate.

As stated above only a relatively small amount of iodine is used in the preparation of ductile zirconium. It serves only as means of transporting the metal from the crude zirconium to the growing rod. It is continually freed at the growing rod, combines again with part of the excess crude metal and "loaded with zirconium" it enters the gas atmosphere again. Care must be taken that the crude zirconium does not contain any great amount of substances like iron, aluminium and silicon, since these substances also form relatively volatile iodides and their presence might lead to contamination of the rods. The oxygen and nitrogen content of the crude zirconium on the other hand is not harmful, since these substances remain behind in the crude metal.

The rods which are prepared according to the process described have a completely compact structure. The specific weight (6.54) determined, with the aid of a hydrostatic balance, agrees accurately with the specific weight deduced theoretically from röntgenographic data. The surface of the rods is composed of well formed crystal planes. *Fig. 2* shows a photograph of zirconium rods 7 mm thick.

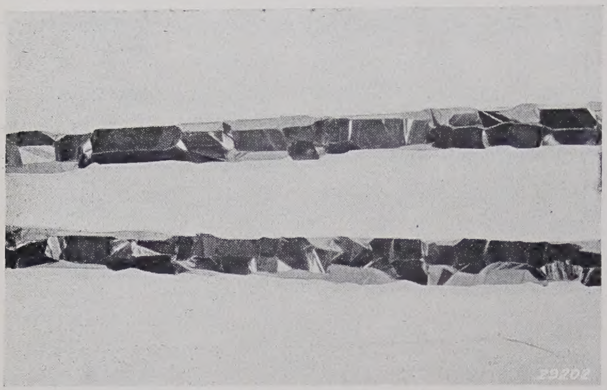
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Fig. 2. Zirconium rods 7 mm thick.

Mechanical working of zirconium

We have already mentioned that the zirconium rods prepared by decomposition of the iodide are so ductile that they may be deformed into thin wire and sheet without it being necessary to heat them. In the preparation of zirconium wire the rods are first swaged with swagging machines to wire of about 0.5 mm thickness. This treatment can be carried out entirely without heating. From the diameter of 0.5 mm the wire is drawn through diamond dies to smaller diameters. If an attempt is made to carry out this process also entirely cold, great difficulties arise. A grating noise is heard during the drawing, while the wire repeatedly breaks. If the wire is examined after drawing under a microscope, grooves are seen in the surface along the whole length. The cause of this phenomenon is that even with careful lubrication particles are torn loose from the surface due to the adhesion between the metal and the surface of the die. These particles remain stuck to the die and are the cause not only of the seizing but also of the continuous rise in the required drawing force to a value which exceeds the tensile strength [3]). If the wire is hot drawn (temperature about 500°C) an oxide film is formed on the wire which is indeed very hard, but which makes drawing possible by preventing seizing. Since we are concerned with a surface phenomenon we can surround the wire with a metal covering instead of the oxide covering. The entirely cold hammering and drawing of rods about 7 mm thick to wire of 30 microns for instance is possible on a technical scale only when a covering of iron, nickel or copper is given to the rods. This covering is then removed chemically (by solution in acid) after the working. Zirconium wire prepared according to this method is entirely free of oxygen and nitrogen, while hot drawn zirconium wire always contains very small quantities of these elements.

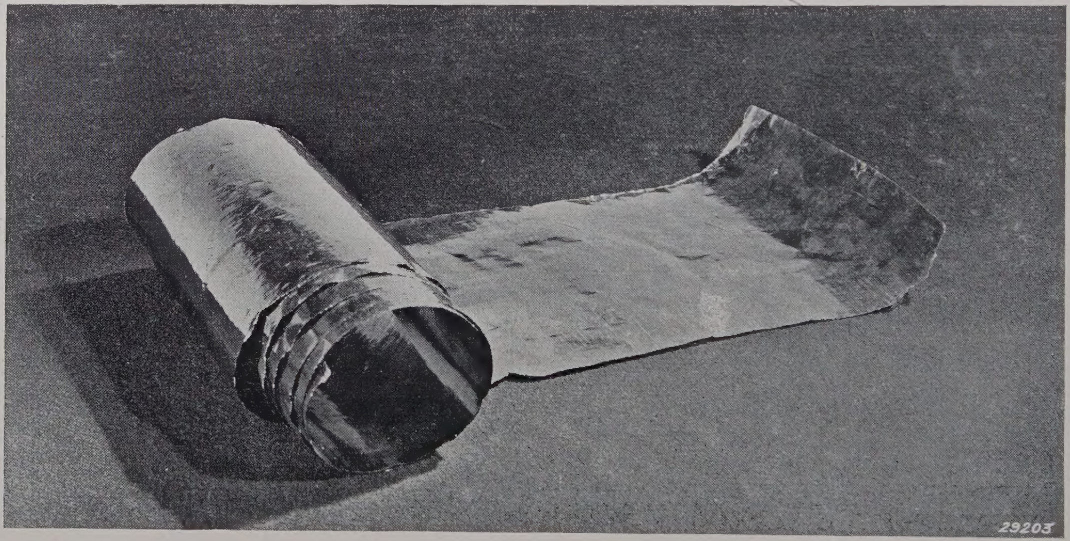
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Fig. 3. Zirconium sheet 20 microns thick, obtained by cold rolling of the material from the thickness of 0.6 mm.

The rolling of the rods to sheet can also be done cold. Usually, however, the rods are hot rolled to a thickness of 1 to 0.5 mm. The surface is then cleaned and the rest of the rolling is done cold. It was found possible in this way to make strips 20 microns thick, 30 cm wide and 1 to 2 m long.

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[3]) It might be expected that the cause of the difficulties in drawing lays in a mechanical hardening occurring during the process. This was, however, found not to be the case, since the same difficulties are also encountered when a zirconium wire is drawn immediately after being annealed in a high vacuum.

If the rolling is done on polished rollers, fine specular sheet is obtained. *Fig. 3* shows a photograph of zirconium sheet 20 microns thick which was rolled from the thickness of 0.6 mm.

It has been found possible to make cold rolled shell bodies of zirconium by the deep stamping process. No particular difficulties arise during drawing when the zirconium sheet which serves as raw material has been rolled in the correct way. *Fig. 4* shows a photograph of three different types of drawn products made of zirconium. *Fig. 5* shows the various stages in making such an article. The processes were carried out cold. Just as in the drawing of wire it was found that bare metal is very difficult to draw, since seizing takes place not only with cold-rolled sheet but also with sheet annealed in a high vacuum. If, however, the material is heated previous to the stamping for a very short time to 650°C in air, a film of oxide is formed which facilitates drawing. The best results are obtained upon heating the metal for only a few seconds in the colourless flame of a Bunsen burner, and then quenching it in water. The metal is then in the form of very fine crystals, since the cold-worked sheet recrystallizes upon heating, while due to the extremely short time of heating there is no appreciable growing together of the very fine crystals formed. This fine grained structure is an advantage for the stamping process.

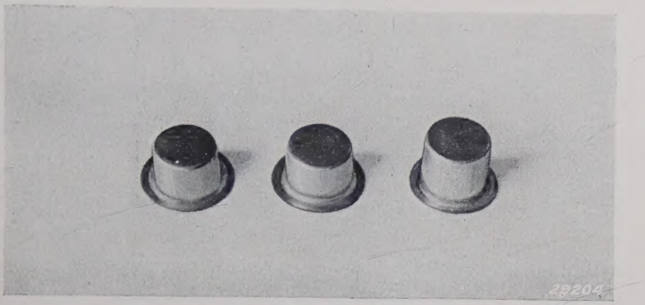

Fig. 4. Shell bodies made of zirconium sheet by application of a deep drawing process.

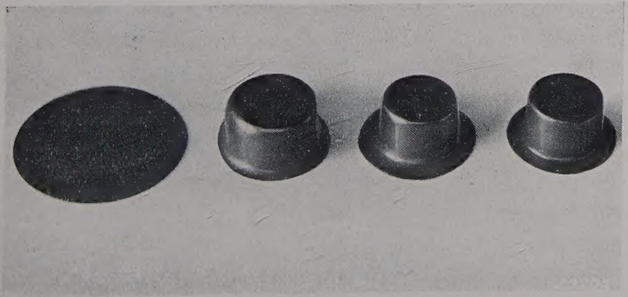

Fig. 5. Different stages in the drawing of shell bodies. The manufacture of the cap (right) from the zirconium sheet (left) requires three processes which can be carried out cold.

Chemical properties of zirconium

The most characteristic chemical property of metallic zirconium is its great affinity for various other elements. Finely-divided zirconium powder ignites when heated above about 200°C in the air, and burns with a blinding white light to give zirconium oxide (ZrO_2). When zirconium is heated in nitrogen a very stable nitride is formed having the formula ZrN. With hydrogen the compound ZrH_2 is formed, which however decomposes again into its elements at relatively low temperatures (above 600°C). *Table I* gives the heats of formation of the three compounds mentioned.

Table I

Compound	Heat of formation k. cals. per mol.
ZrO_2	258
ZrN	82
ZrH_2	40.5

If the metal is not allowed to react with an excess of gas, but with quantities in a closed space, it is found that large quantities of gas can be taken up without a new phase being formed. In the reaction with nitrogen the cubic phase of the nitride is formed in addition to the hexagonal phase of the metal only after the nitrogen content has exceeded about 20 atom per cent. The first 20 per cent are thus taken up in solid solution. For oxygen the limit of solid solubility even lies at about 40 atom per cent, while for hydrogen it is already reached at 5 atom per cent.

In the investigation of the systems zirconium-oxygen, zirconium-nitrogen and zirconium-hydrogen it is best to begin with ductile zirconium rods or bare wires which are made by cold working of the rods. In the case of the systems with oxygen or nitrogen the wires must be heated for some time at a high temperature after taking up the different amounts of gas in order to reach complete homogeneity. The simplest method of heating is by the passage of a current. When the content of gas is not too high the solutions formed cannot be distinguished in appearance from the pure metal. When unworked rods are used the solutions still exhibit the same crystal planes and the same high metallic lustre. *Fig. 6* shows two pieces of the same zirconium rod (thickness about 3 mm). The shorter piece has been kept in the original state and is therefore quite pure and very ductile. The longer contains 13 atom per cent of nitrogen and is very brittle. Superficially, however, the two pieces cannot be distinguished from each other.

If wires containing several atom per cent of oxygen, nitrogen or hydrogen are heated in a high vacuum, it is found that the hydrogen can be driven out quite easily. (The removal of the last traces, however, takes a long time even at a high temperature). Oxygen and nitrogen, however, cannot be driven out. Upon increase of temperature the gas pressure remains zero, and at temperatures near the melting point metal atoms begin to evaporate, while the oxygen or nitrogen remains in the wire. These gases are therefore also bound by strong chemical forces when they are present in the metal in the dissolved state.

The specific weight of zirconium is increased by the introduction of oxygen or nitrogen atoms into the metal lattice. From this it may be concluded that these atoms lie in the open spaces of the metal lattice. They are probably quite irregularly distributed throughout the lattice. In *table II* are the results of several determinations of volume and specific weight (of rods 3 mm thick) before and after the taking up of known amounts of nitrogen or oxygen.

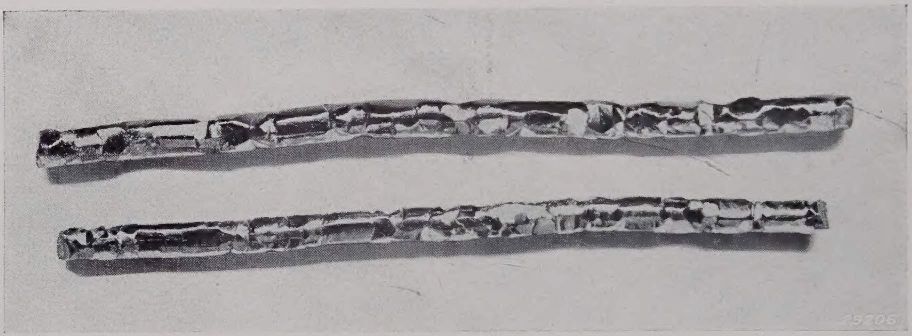

Fig. 6. Two pieces of the same zirconium rod. The shorter piece is chemically pure and very ductile. The longer piece was heated in an atmosphere of nitrogen, it contains 13 atom per cent of nitrogen and is very brittle. In appearance the two pieces cannot be distinguished from each other.

Table II

Composition in atom per cent	Volume increase	Specific weight
100% Zr		6.540
98 % Zr + 2 % O	0.15%	6.555
98 % Zr + 2 % N	0.23%	6.546
90 % Zr + 10 % O	1.05%	6.600
87 % Zr + 13 % N	1.72%	6.577
78.5% Zr + 21.5% O	1.51%	6.755

The temperature coefficient of the electrical resistance decreases upon the solution of oxygen or nitrogen in the metal. The values given in *table III* were measured.

Table III

Composition in atom per cent	Temperature coefficient of the electrical resistance
100% Zr	0.00445
98% Zr + 2% O	0.00264
98% Zr + 2% N	0.00261

For oxygen and nitrogen therefore the same lowering of the temperature coefficient was found.

Applications of metallic zirconium

Mixed with one or more oxidation agents finely-divided zirconium is used as a flash light powder.

Several other applications of zirconium are also based upon the property of this element of reacting easily and rapidly with various gases, with the result that the gas pressure falls to zero if there is an excess of metal. For this reason it is used as a getter in discharge tubes, especially in transmitting valves. The zirconium must be placed in the tube at such a spot that it assumes the required temperature at the moment when its function of combining with the gas must be exercised, or it must be at such an electric potential that the gas ions formed strike the zirconium and are then held bound. The favourable action of the zirconium is manifested in two ways. In the first place the times of evacuation during manufacture are considerably shortened because the zirconium also acts as a pump. In the second place the small amounts of gas which may be freed when the discharge tube is in use are immediately bound. The temperature which the zirconium must assume depends upon the nature of the gas to be absorbed and in addition on the nature of the zirconium itself. If ductile (and therefore compact) zirconium is used, and if the freeing of gases like oxygen, nitrogen, carbon monoxide and carbon dioxide must be taken into account, it is desirable to have the temperature as high as possible (1400°C for example). Hydrogen, however, is given off again for the most part at this high temperature (an equilibrium pressure is established). The optimum temperature for taking up hydrogen is 300 to 400°C, in which temperature range a solid solution of hydrogen in zirconium has no appreciable gas pressure, while the absorption velocity is already very high. Therefore if provision must be made not only against the freeing of oxygen, etc., but also against the freeing of hydrogen and water vapour, it is desirable to have present in the tube, in addition to the zirconium heated to a high temperature, a portion of zirconium with a temperature of 300 to 400°C. It is often possible to combine these two requirements by introducing the zirconium at such a spot that different parts of the metal are raised to different temperatures so that the temperature range extends from 300° to for instance 1400°C.

In many cases metallic zirconium can also be used in the form of a fine powder which may for instance be applied to the anode of a transmitting valve. The finely-divided zirconium reacts with the different gases at a considerably lower temperature than compact zirconium.

The fact that zirconium may contain large quantities of oxygen and nitrogen in solid solution is a great advantage when the metal is used as a getter. At sufficiently high temperature there is no layer of oxide or nitride formed which hinders further taking up of gas, but the oxygen or nitrogen diffuses to the inside and the metal surface always remains clean.

A quite different property of zirconium which is important for its use in transmitting valves is the small value of its secondary emission. By making the control grid of a transmitting valve of zirconium, or covering it with zirconium, the secondary emission of this grid can be diminished to a negligible value. The zirconium used for this purpose also retains its property of combining with gases. By covering a grid of molybdenum or tungsten with zirconium oxide, the secondary emission of the grid may also be sufficiently reduced. For further particulars about this action of zirconium the reader is referred to an article by H. G. Boumeester in this periodical (Philips techn. Rev: 2, 115. 1937).

Although zirconium, as may be seen from the above, combines readily with all kinds of elements or reacts with all kinds of compounds at higher temperature (depending on the form of the metal), the compact metal is remarkably inert at ordinary temperatures. This inertness must be ascribed to a film of oxide which is formed on the surface and cannot dissolve in the metal at ordinary temperatures. This oxide film, which is quite invisible, protects the metal to such an extent, that zirconium keeps its lustre under all circumstances and is not attacked by acids, bases or other corrosive agents (except hydrogen fluoride). Thanks to this property zirconium is a very suitable metal for use in chemical processes where other metals would quickly corrode. For example in the etching or cleaning of metal articles which must be immersed successively in alkali and acid baths, zirconium wire is used to hang up the articles as it does not corrode and does not contaminate the baths, while in electrolysis it may also serve as supply line for the current.

The refractory compounds of zirconium

The oxide, the nitride and the carbide of zirconium melt at considerably higher temperatures than the element itself, as may be seen from *table IV.*

Table IV

Substance	Melting point, °C
Zirconium, Zr	1860°
Zirconium oxide, ZrO_2	2700°
Zirconium nitride, ZrN	2980°
Zirconium carbide, ZrC	3530°

The oxide dissolves poorly in glass and is therefore used to render glaze and enamel opaque. It is also used in the manufacture of very refractory articles in the form of crucibles, tubes, boats, fire bricks, insulators, etc. These articles can be used at temperatures considerably higher than 2000°C. In addition to its high melting point the small coefficient of expansion and the chemical stability are important in this connection. If the products are made of pure ZrO_2, they show a tendency to develop cracks upon heating due to the transition at 1000°C from a monoclinic to a tetragonal modification, which is accompanied by a contraction of 7 per cent in volume. If the zirconium oxide is mixed with a few per cent of magnesium oxide, a homogeneous cubic solid solution is formed upon heating above 1700°C, which is subject to no changes in modification, and which therefore can be used for the manufacture of very highly resistant refractory articles. Instead of magnesium oxide other substances may also be used, calcium oxide or thorium oxide for example. Beryllium oxide with zirconium oxide forms an eutectic system without the formation of solid solutions. With the help of this compound it is therefore impossible to suppress the reversible change in modification of ZrO_2, since we have to do with mechanical mixtures in the whole system. However, when BeO is used in combination with MgO (for instance 2 per cent MgO + 0.5 per cent BeO), it seems to give a more satisfactory result than MgO alone.

Because of the increasingly high requirements being made of many ceramic products with respect to their resistance to heat, it is probable that many possibilities for the application of ZrO_2 will still be found.

Zirconium carbide, ZrC, is one of the few substances which have a higher melting point than tungsten. In the history of the electric light bulb industry this compound has played a part. In addition to a high melting point it has metallic electrical conductivity so that it could be used for filaments of electric lamps. Upon the invention of the tungsten lamp, however, the compound passed out of use. It was discovered later that a mixture of 4 parts of tantalum carbide and 1 part of zirconium carbide forms a material with the highest melting point of any known substance. The two carbides form an uninterrupted series of solid solutions with a maximum melting point at the composition mentioned. The melting point of this mixture is almost 4000°C (At the same high temperature a mixture of 4 parts tantalum carbide and 1 part hafnium carbide melts). Zirconium carbide is also one of the metallic carbides with a very great hardness, for which compounds there has been great interest in recent years in connection with the important applications which the carbides of tungsten, tantalum and titanium have found in the working of metals.

QUANTITATIVE CONSIDERATIONS OF ELECTRIC WELDING

by J. ter BERG.

In ordinary welding with a rod provided with an oxidizing coating, it could be shown that 82 per cent of the fused metal core is used in the weld, 12.5 per cent is lost by spattering and about 4.5 per cent is lost due to oxidation by the coating, while evaporation plays only a minor part. If instead of the ordinary atmosphere, nitrogen or compressed air is used as gas environment, little change is observed: more or less iron is then also oxidized by the flux. When a mixture of hydrogen and nitrogen is used, this reaction does not take place at all. It has been shown clearly by these experiments, that in the attempt to increase efficiency care must be taken not only to have a low loss from spattering, but also that the coating of the rod should possess little or no oxidizing power, or that this coating should give off gases during welding which form a reducing atmosphere around the arc.

Introduction

It is a well known fact that in electric welding a certain percentage of the metal used is lost in some way or other. What may be the causes of this loss of material, and to what extent each cause may contribute to the total loss, has not, as far as is known to the author, been dealt with in the literature in the case of coated welding rods. The experiments and calculations described below were carried out for the purpose of procuring data on this problem.

The term efficiency is used here, and by the efficiency of a welding rod we mean the ratio between the weight of the metal found in the weld and the weight of the core metal consumed in making the weld.

The rods specially made for our experiments contained a malleable iron core with a diameter of 5 mm, while the coating consisted of ferrous and ferric oxide, quartz and aluminium silicate with potassium water glass as a binder. The average efficiency of several tests carried out under ordinary conditions was low and amounts for these rods about 82 per cent.

The question is, what has happened to the remaining 18 per cent? The following causes of loss of metal may be listed:

a) evaporation
b) spattering
c) reactions of molten metal with liquid slag.

We shall deal with these three factors in succession.

Evaporation

Quantitative data on this factor were obtained by sliding a copper jacket over the piece of work during welding. The vapours developped are deposited on the copper. Although the amount of evaporation of core and coating were determined together in this way, it was found from the weight of material deposited - which consisted chiefly of iron oxides - that the evaporation of the metal plays a very small part, and cannot in any case account for a loss of core metal of more than 0.5 per cent.

Spattering

The loss of metal due to spattering was determined by making a weld 2 cm wide on a strip 2.5 cm wide, with the strip laid on a large thick copper plate. In this way practically all of the spattered drops fell on the copper plate to which they do not adhere, so that they may easily be removed and weighed. The diagrammatic representation in *fig. 1* illustrates the arrangement employed.

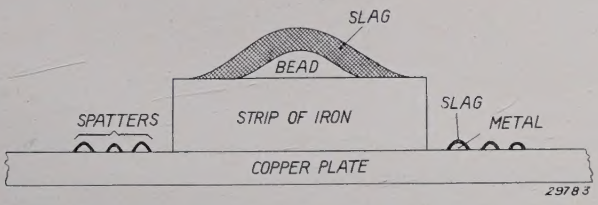

Fig. 1. Arrangement for the determination of the amount of metal spattered away during welding.

Before welding is started, the weight is determined of the strip, of the iron core and of the coating. The weight of the latter could be determined by weighing the iron core before and after it was coated. The following weights were determined after welding:

1) The weight of the remainder of the iron core. This determined the weight of metal fused down;
2) The weight of the remainder of the coating. This gave the weight of the coating fused down;
3) The weight of the slag on the weld (*fig. 1*) which could be separated quantitatively from the metal;
4) The weight of the strip with the weld, from which the weight of the weld and the efficiency could be calculated;
5) The weight of the spatters which consisted of drops of metal surrounded by a layer of slag. Under the entirely reasonable assumption that the ratio of weights of metal and slag is the same for the spatters as for the weld, the weight of the spattered metal could be calculated.

This is presented in a clearer form in *table 1*, in which are given the results obtained in welding with three rods of the type described above. It also appears from the table that the agreement among the three columns is so good that the average values may certainly be assigned real significance.

Table I

	I	II	III	average
Fused metal	52.5 g	53.4 g	55.5 g	53.8 g
Fused coating	18.0	19.2	19.5	18.9
Metal in the weld . . .	43.7	44.1	44.8	44.2
Slag on the weld . . .	18.4	18.8	18.0	18.4
Total weight (metal + slag) of the spatters .	8.7	9.8	9.0	9.2
Metal in the spatters *) .	6.1	6.9	7.0	6.7
Slag in the spatters . .	2.6	2.9	2.0	2.5
Total fused slag . . .	21.1	21.7	20.0	20.9
Effic. $= \frac{\text{Metal in weld}}{\text{Metal fused}}$	83.2%	82.6%	80.7%	82.1%

*) Calculated as follows: $\frac{43.7}{43.7 + 18.5} \cdot 18.7 = 6.1$

It may immediately be deduced from this table that the loss by spattering amounts to 12.5 per cent of the weight of metal fused from the rod.

Reactions of molten metal with liquid slag

The average efficiency, as may be seen from table I, was 82.1 per cent. Therefore about 18 per cent of the original core material is lost. As given above, evaporation and spattering cause a loss of 0.5 + 12.5 = 13 per cent. The disappearance of the remaining 5 per cent of the core material may be explained by assuming that the liquid iron reacts with the Fe_2O_3 of the molten slag. This assumption may immediately be tested qualitatively by the fact that the total weight of the slag is greater than the weight of coating fused, which indicates a slag formation by a part of the molten iron.

Quantitatively also the above assumption corresponds to the values given in table I. The following consideration will make this clear.

By a ferro-ferri analysis it was shown that the 18.9 g of coating melted contained 2.6 g FeO and 8.5 g Fe_2O_3, while there was 12.1 g FeO and 1.2 g

Fe_2O_3 in the slag. Therefore 8.5—1.2 = 7.3 g Fe_2O_3 disappeared during the welding process. If we now assume that it reacted as follows with the iron:

$$\begin{array}{l} Fe_2O_3 \rightarrow 2\ FeO + O, \\ Fe + O \rightarrow FeO \qquad , \\ \hline Fe_2O_3 + Fe \rightarrow 3\ FeO, \end{array}$$

then the 7.3 g Fe_2O_3 has used 2.5 g Fe from the core to form 9.8 g FeO which is taken up in the slag. The fact that the reaction occurred in this way is confirmed by the consideration that according to this calculation the slag should contain 2.6 + 9.8 = 12.4 g FeO, while analysis shows very good agreement with 12.1 g FeO. Moreover, the whole "welding account" is now balanced, since, from the foregoing calculations, of the 53.8 g of iron which was melted down the following amounts were used:

in the weld:	44.2 g =	82.1%,
evaporated (maximum): . . .	0.3 g =	0.5%,
spattered:	6.7 g =	12.5%,
slag formation with the coating:	2.5 g =	4.8%,
Total . . .	53.7 g =	99.9%.

Now that we have obtained a quantitative idea about the distribution of the metal fused down over the various forms which it takes on during welding, the following point must be noted. One of the great advantages of a coated welding rod over a bare rod is usually considered to lie in the fact that the oxygen and nitrogen of the air are so well kept away during welding that they have no opportunity of contaminating the metal, and thus unfavourably affecting its mechanical properties. It will, however, immediately be seen that in the case here studied, where the coating contains ferric oxide [1]), a primary oxidation of the metal must occur, since oxygen gas is freed during the welding process and comes into direct contact with the liquid iron. Even if the slag prevents the entrance of oxygen from the air, it cannot prevent the oxidation of the iron. The advantages of a coated welding rod over an uncoated one must be sought in other directions. Much more attention must be given to the solution of the oxides present and those newly formed in the liquid slag, while under certain conditions a stream of strongly reducing gas is generated in the coating, which surrounds the arc during welding and may exert a favourable influence on the oxygen content of the metal. In any case the idea that the slag protects the molten metal from the action of oxygen is in its general form incorrect.

It is also a question whether the slight nitrogen content of a weld made with a coated rod can be adequately explained by the mechanical shielding action of the liquid slag and the mantle of gas formed; it is possible that processes similar to the one discussed above also play an important part.

Welding in different atmospheres

The results given in the foregoing were of such a nature that a decision was made to carry out the welding process in other atmospheres than air. For this purpose use was made of a very simple piece of apparatus shown in fig. 2. During welding the apparatus was gradually pushed up, so that as the rod melted off, the arc was surrounded by

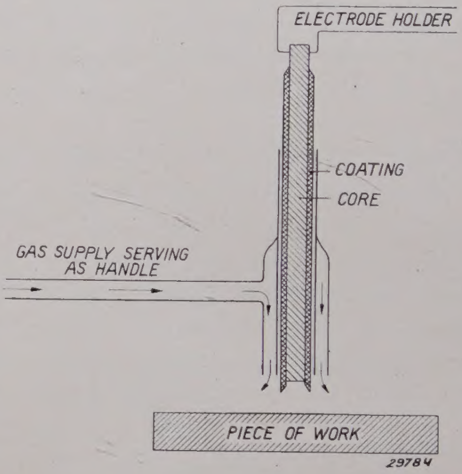

Fig. 2. Apparatus for welding in different atmospheres.

Table II

	A ordinary	B nitrogen	C compressed air	D 75% N_2 + + 25% H_2
Metal fused	100 g	100 g	100 g	100 g
Coating fused	35.3	33.2	31.9	31.0
Metal in the weld. . .	82.1	81.7	75.7	84.1
Slag on the weld . . .	34.2	30.2	36.7	24.6
Total weight (metal + slag) of spatters . .	17.1	17.7	17.8	19.0
Metal in spatters . . .	12.5	13.0	11.9	14.6
Slag in spatters	4.6	4.7	5.9	4.4
Total slag melted . . .	38.8	34.9	42.6	29.0
FeO of coating	4.8	4.5	4.3	4.2
Fe_2O_3 of coating . . .	15.8	14.9	14.5	13.9
FeO of slag	22.3	20.5	23.9	15.8
Fe_2O_3 of slag	2.3	1.7	5.5	1.4

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[1]) Besides this oxide there are many other substances which are often used in the coating, and which give off free oxygen during the welding process. There are for example the carbonates, which certainly show oxidizing properties at the high temperature of the arc.

the gas in which the test was being made, and the gas was supplied at a definite rate. Compressed air, nitrogen and a mixture of 25 per cent hydrogen and 75 per cent nitrogen were used.

Table II gives the results of these experiments together with those obtained in ordinary welding; the different quantities are here again averages of several observations, and for ease in comparison they are all re-calculated for 100 g of metal fused, so that the amount of spattering and the efficiency for example may be read directly in per cent of metal fused.

We shall deal separately with the four columns of this table.

A. Ordinary atmosphere. During the process of welding 15.8—2.3 = 13.5 g Fe_2O_3 disappeared. This reacted with the liquid iron according to the following equation:

$$13.5\text{ g } Fe_2O_3 + 4.3\text{ g } Fe \rightarrow 17.8\text{ g } FeO$$

There was present in the coating 4.8 g FeO

The slag must therefore contain 22.6 g FeO

Analysis of the slag gave 22.3 FeO, thus good agreement. Therefore 4.3 per cent of the iron went into slag formation, and this is manifested in the increase in weight of slag with respect to weight of the coating melted.

B. Nitrogen atmosphere

Reaction . . 13.2 g Fe_2O_3 + 4.2 g Fe → 17.4 g FeO

There was present in the coating 4.5 g FeO

Total calculated 21.9 g FeO

Analysis showed 20.5 g FeO. This slightly too low result may, however, be explained by the fact that some of the oxygen of the decomposed Fe_2O_3 does not react with molten iron but under the conditions of the experiment escapes as free oxygen or in the form of oxides of nitrogen.

C. Compressed air

From the values found it may immediately be deduced that in addition to the normal oxidation of the liquid iron by Fe_2O_3, the oxygen of the surrounding air also exerts an oxidizing action. A large increase in weight of the slag may be observed with the resulting lowered efficiency.

D. Reducing atmosphere

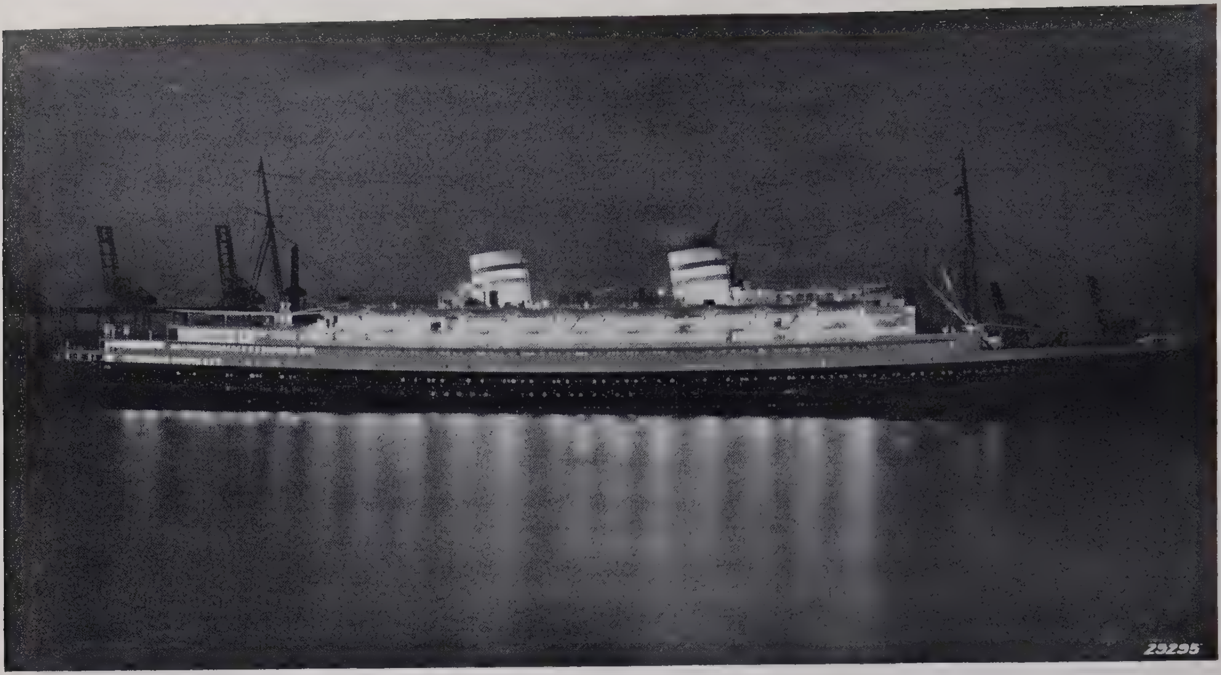
This case is particularly interesting in connection with welding with a so-called "shielded arc", where an attempt is made to surround the arc with a reducing gas. It may be seen from the values given in the table that there was a decrease in weight of the slag, in contrast to the previous cases where an increase in weight of slag with respect to original coating was observed.

This difference can now be explained simply by assuming that the oxygen freed from the Fe_2O_3 no longer reacts with the iron, but with the surrounding hydrogen with the formation of water which escapes, in the following way:

$$Fe_2O_3 + H_2 \rightarrow 2\,FeO + H_2O\nearrow$$

Since the molten iron is protected against oxidation in this way, there will be increased efficiency, and this will be manifested as a decrease in weight of the slag with respect to the weight of coating melted.

Quantitatively also the calculation and experiment may be shown to agree. During the welding process 13.9—1.4 = 12.5 g Fe_2O_3 disappeared and were decomposed into 11.2 g FeO and oxygen. According to the calculation therefore the slag should contain 11.2 + 4.2 = 15.4 g FeO, while analysis gave good agreement with 15.8 g FeO.



THE ILLUMINATION OF PASSENGER SHIPS

by L. C. KALFF.

628.972:629.123.3

In connection with the installation of the lighting system of the s.s. "Nieuw Amsterdam" the most important problems are discussed which are encountered in such a case. A series of photographs give some impression of the results achieved.

It is not so long ago, that the problem of illumination was almost entirely neglected during the designing and building of passenger ships. And when it was finally considered, economy was held to be the main essential, economy in the number of lamps, in the power installed and in the method of illumination. An attempt to achieve technically satisfactory illumination with the avoidance of too great differences between light and dark was not valued, and no attention was paid to uniformity and harmony in the illumination.

Nowadays ideas have been changed, at least with respect to the illumination of the luxurious modern ships. In the case of such ships the main aim is now that the passengers should be offered the same comforts as the guests of a first class hotel. A pleasing, adequate and efficient illumination certainly belongs among such comforts. Fortunately modern lamps and fittings are more economical than earlier ones, and therefore with the same wattage the number of lumens available is larger. Moreover with the present fast liners the power consumed by the lighting system, even when it is very generously designed, constitutes only a small percentage of the energy necessitated for propulsion.

For reasons of safety 65 volts was usually chosen as working voltage for the lighting system. In the present huge ships the diameter of the connections would have to be very great with this working voltage, because of the much greater length of cable. A higher voltage, 125 volts for instance, is therefore chosen. An advantage of this voltage over a still higher one lies in the fact that with it the lamps are much better able to withstand shocks and vibrations.

In designing the illumination of a ship the main interest naturally lies in the various parts of the ship which are used by passengers, *i.e.* cabins, corridors, dining rooms and recreation rooms. In the first place the desired level of illumination must be decided upon, as well as the system for each individual type of room or corridor. Moreover the mutual relation of the intensities of illumination in these different places must so be chosen that no disturbing transitions are encountered in passing from cabin to corridor or from vestibule to hall. Such transitions might lead to dazzle, or, if the transition is from a better lighted portion to a less well-lighted one, it would make a somber and unpleasant impression.

In the cabins (*figs. 1* and *2*), where the passengers must be able to see everything with ease, and where they dress and sometimes even read, a general diffuse lighting with no dark corners is desired. Light-coloured walls may contribute to this effect. An intensity of illumination of 85 lux (8 foot-candles) is certainly necessary.

If a cabin is compared with a good hotel room, then, within certain limits which make the fixing of this value somewhat arbitrary, this level of illumination of 85 lux is arrived at. For ships which sail in tropical waters an exception must be made. In this case the ventilators succeed in reducing the temperature a few degrees only with the greatest difficulties. The heat development of many electric lamps would make the work of ventilation more difficult, and the direct radiation would be particularly disagreeable. In such cases, therefore, small light sources are now used which give sufficient local illumination, above the toilet mirror, on the writing desk and the side of the bed in the form of a reading lamp. A fundamentally different solution would be the use of discharge lamps which, in contrast to ordinary electric lamps, may be said to give "cold light".

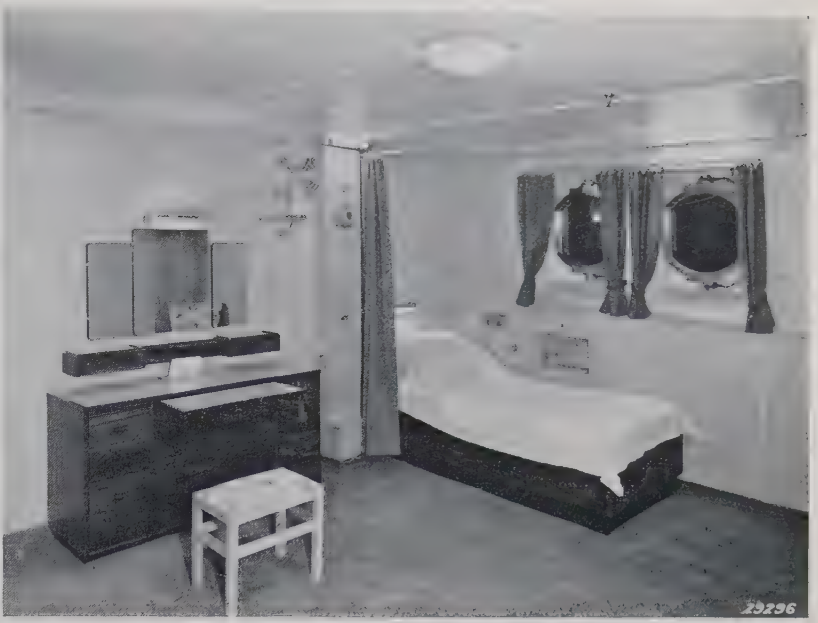


Fig. 1

Figs. 1 and 2. For the cabins on board the "Nieuw Amsterdam" an average intensity of illumination of 85 lux was assumed to be necessary. For practical reasons (the lowness of the ceilings) use had to be made of many small units. The cabins have double ceilings so that special built-in plafonniers could be used. These can hold two or three horizontally mounted lamps of 65 Dlm. The bowl of opal glass projects 7 cm from the ceiling. This prevents strong contrasts, while the chance of damage during the carrying in of trunks is still very small. Where it seemed desirable opal glass "Philinea" tubular lamps of 25 and 40 W (30 and 50 cm long) were introduced, for instance above the toilet mirror, the writing desk, etc. These lamps are so mounted as to be fairly free of vibrations, and thus last as long on a ship as under ordinary conditions. There are also lamps in the closets which are switched on and off automatically by the opening and closing of the doors.

In ordinary cases, however, the level mentioned of 85 lux (8 ft. cdl.) may be retained as a standard. If this level is used in the cabins, the other rooms may be compared with them.

A certain degree of economy may very well be observed in the case of the corridors (*fig. 3*), where light is burning day and night, and where the total length is so great. The level may not of course be so low that upon coming out of brightly lighted rooms such as cabins, one can no longer see clearly. Taking the level of 85 lux (8 ft. cdl.) for the cabins into account, a level of 40 lux (3.7 ft. cdl.) for the corridors may be said to be satisfactory.

The vestibules (*fig. 4*) and the dining rooms (*fig. 5*) must be festively and decoratively lighted. A high level of illumination of for

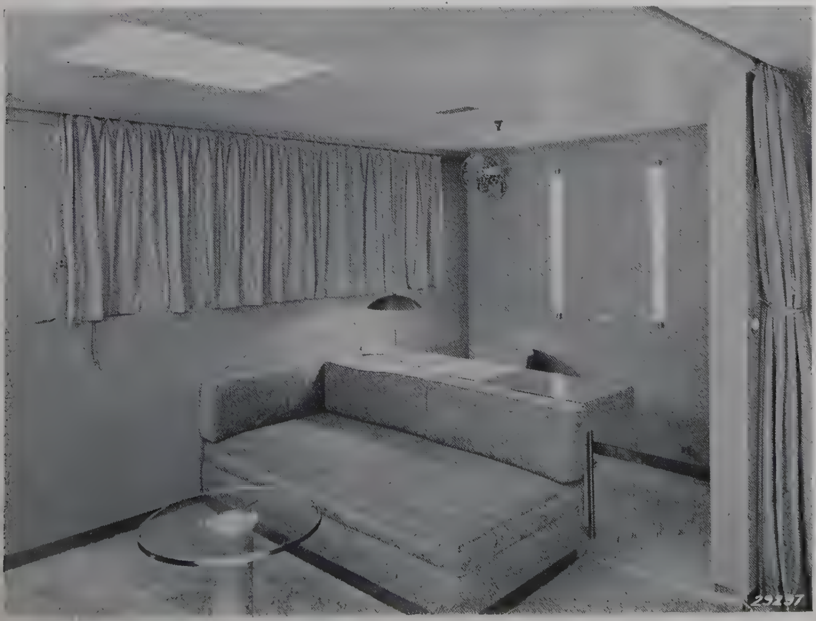


Fig. 2

Fig. 3. A corridor on board the "Nieuw Amsterdam". There was here little choice possible in the type of illumination. The ceilings consist of large trap doors on hinges, behind which are the connection lines. The walls must be kept as smooth as possible because upon embarcation there are always many porters passing along the fairly narrow corridors with heavy trunks on their backs. For this reason "Philinea" lamps were used which occupy very little space; they are installed in the angle between ceiling and wall in a horizontal position above every door. In this way a fairly uniform illumination of 40 lux on an average is obtained.

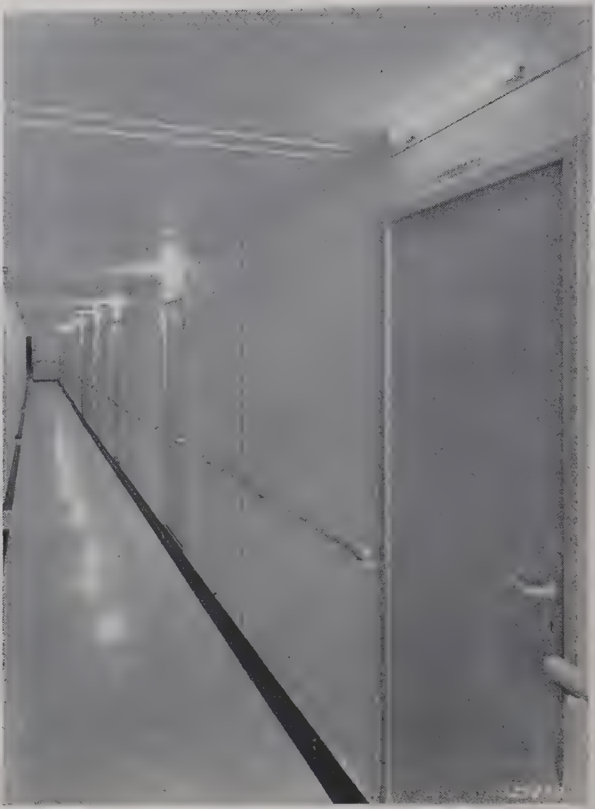
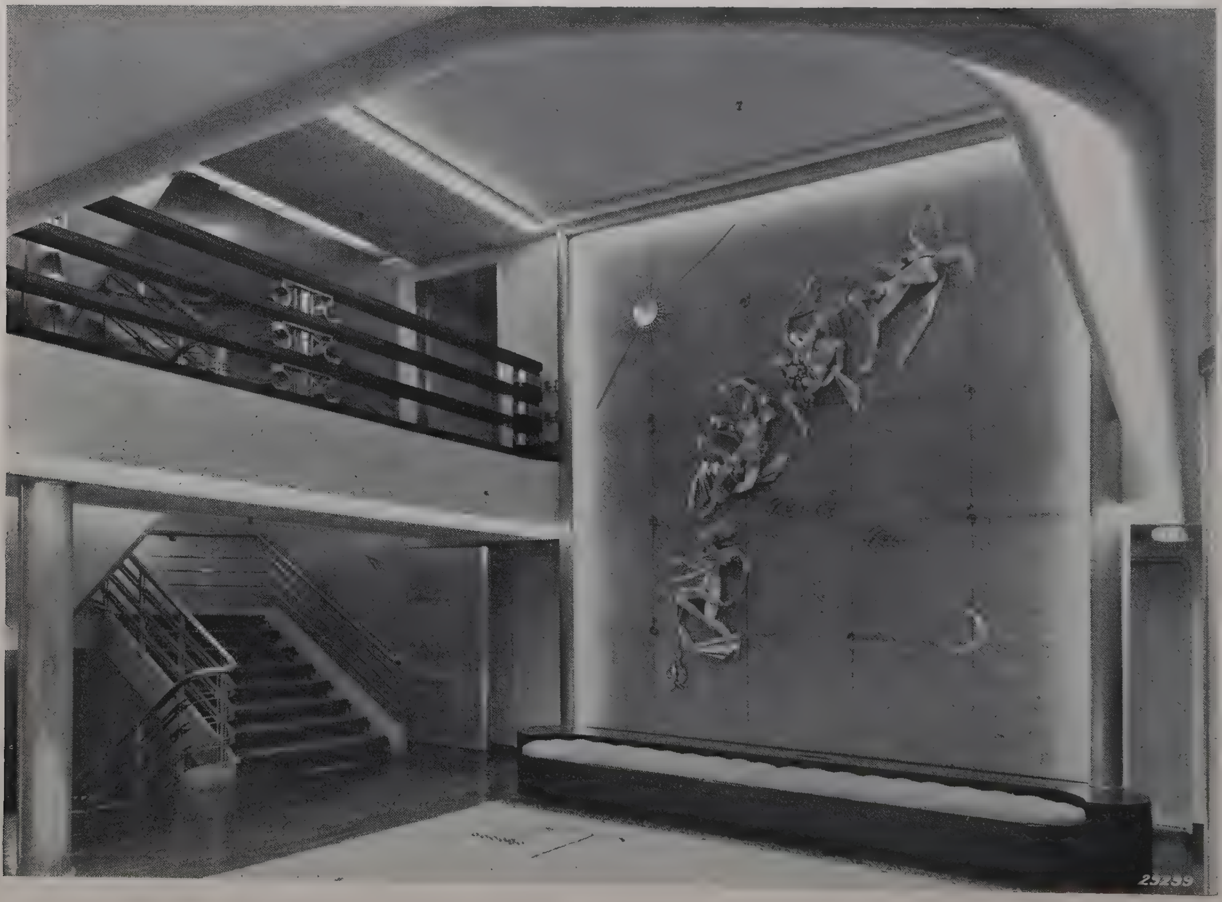


Fig. 4. Large vestibule of the "Nieuw Amsterdam". This vestibule often serves as entrance hall for those embarking from the dock. In this case the height of two decks was available, which made it easier to reach a satisfactory uniformity in the illumination. The light-coloured ceiling and the almost white floor covering also contribute to this result. At the height of each deck there is a continuous line of "Philinea" tube lamps around the vestibule, while on the stair side there is an additional row of "Philinea" lamps behind matt glass plates. The intensity of illumination is 100 lux on an average. The relief in dull gilded metal on a background of green patiné bronze is lighted from the edges by a row of lamps in a light cove (75 lamps of 25 W).



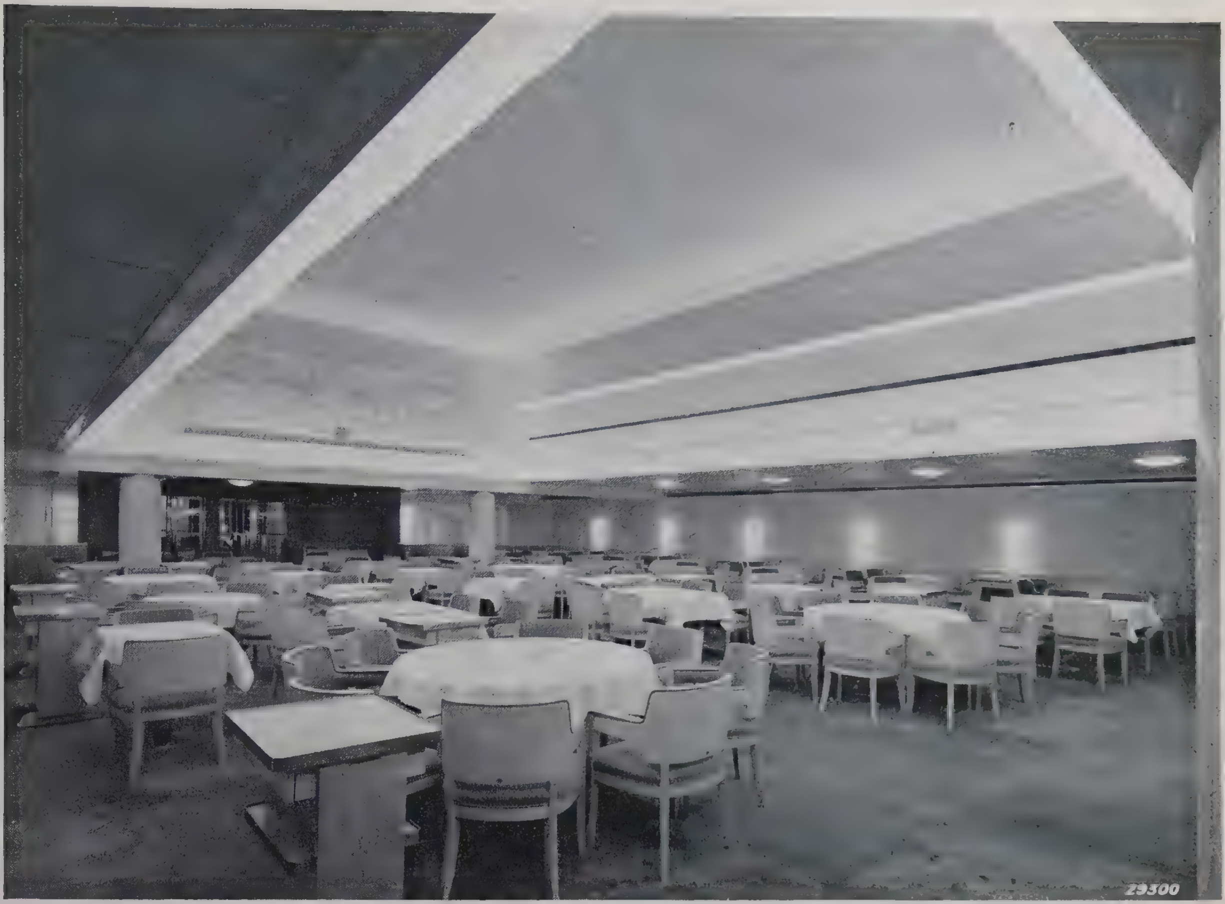


Fig. 5. Dining room of the tourist class of the "Nieuw Amsterdam". The main illumination is semi indirect, and consists of a light-cove of Venetian glass, which runs around the higher middle portion of the ceiling. The glass is composed of glass rods containing air bubbles which are fused together and bent, thus forming elements 12 cm wide. These elements are mounted in a row side by side and are alternately very pale green and pink in colour. Since the points of light are faintly visible through the glass the lamps must be placed at regular intervals behind the glass. There are in all 172 lamps of 40 W installed in the recess. The surrounding lower-ceilinged portion of the room is lighted by 24 plafonniers and 16 wall appliqués of the same Italian glass each containing 3 lamps of 40 W. The intensity of illumination in the middle of the room is 110 to 150 lux, in the lower portion 45 lux. The illumination also serves to bring out the two large bas-reliefs at the ends of the room.

example 120 lux (11.1 ft. cdl.) is desired in the middle of the rooms at table height. A higher level of 120 to 200 lux (11.1 to 18.6 ft. cdl.) is suitable for the ball room as well as for writing and reading rooms and card rooms. A smoking room, on the other hand, were the main object is restfulness, requires no more than about 60 lux (5.6 ft. cdl).

When the main level of illumination has been fixed upon, attention must be given to the systems of illumination. A system of direct lighting is suitable in the cabins as well as in the corridors. In the larger halls a combination of direct and indirect lighting will be chosen in order to obtain uniformity. The occurrence of reflections then improves the appearance of table silver, ladies' toilets and jewels. In other cases (*fig. 5*) recessed lighting was chosen.

In carrying out the details of the plan thus established, a choice must be made of types of lamps and fixtures in order to obtain the desired results. In doing this the lowness of the ceilings presents a problem which is typical of ship illumination in general. It is therefore necessary to place the sources of light against the ceiling or even partially in the ceiling, so that the ceiling itself is partially unilluminated. Since in addition the rooms often have a relatively large floor space, the angles at which the light is reflected from the walls upon the usually horizontal surfaces to be illuminated are generally unsatisfactory, so that the contribution from the walls is only slight.

Under these circumstances it is not easy to achieve a uniform illumination without disturbing local contrasts. Where there are double ceilings, specially designed built-in plafonniers are used. The fitting constructed for this purpose can hold two or three lamps of 65 Dlm in a horizontal posi-

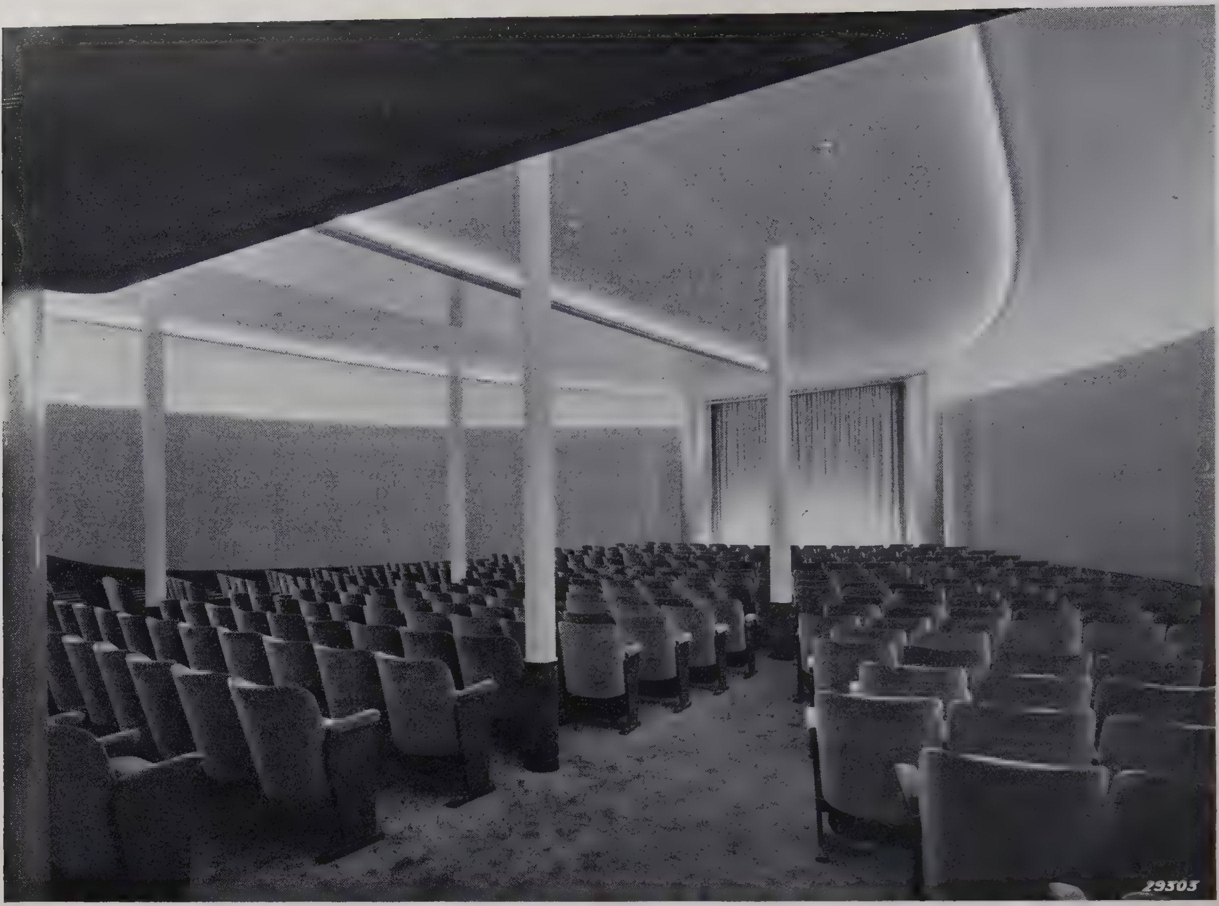


Fig. 6. Illumination of the theatre and cinema hall of the "Nieuw Amsterdam", which seats 350 persons. In order to lose nothing of the height the illumination had to be built into the walls and ceiling. A continuous line of tube lamps was installed along the three narrow bands where the slightly curved surfaces of the ceiling meet. In addition a light recess was made above the wine-red wainscoting, and equipped with a double row of tube lamps.

tion, and has a rosette which is sunk 3 cm into the ceiling. The opal glass bowl then projects only 7 cm from the ceiling. Because of this slight projection, damage to the bowls in carrying large steamer trunks into the cabins is avoided. With the same purpose in view the illumination of the corridors is carried out with tubular lamps placed as high as possible above the doors.

These opal glass "Philinea" tubular lamps of 25 and 40 W (30 and 50 cm long) are also installed in the cabins wherever it seemed necessary, in addition to the plafonniers of which there are one, two or three according to the size of the cabin. They are mounted in fittings with pistons having a double spring action, and are therefore fairly free of vibration. Besides in the corridors these tubes are also found above the toilet mirror and writing desk, and a corner of the cabin where one might wish to sit and read and beside the mirrors over the wash hand stands. Fastened to the wall over the beds there are small shaded reading lamps with small tubular lamps of 25 W.

In order to illustrate the various types of illumination we include a series of photographs taken on board the "Nieuw Amsterdam" of the Holland-America Line. The illumination was designed by the Philips consulting bureau for illumination and the technical staff of the steamship line, in collaboration with all the architects and decorators who

Fig. 7. The "Grand Hall" of the "Nieuw Amsterdam". This is the fashionable meeting place of the guests before and after dinner. The lighting is entirely indirect. The hall is decorated in light grey, as a suitable background for the colourful toilets of the ladies and the black and white of the gentlemen. The light is projected over uniform grey backgrounds from behind all the decorated surfaces of the walls and ceilings. Behind the pilasters and mural paintings there are continuous lines of tube-lamps; behind the lowered ceiling, executed in cast aluminium, there are rows of 40 W lamps with 4 lamps per metre. In front of the pilasters there are 4 large glass bowls and in the colums near the entrances to the hall there are 4 reflectors which provide for the further illumination of the ceiling.

Fig. 8. Third class smoking room of the "Nieuw Amsterdam". In this room a different solution has been found of the problem of introducing variation into the lighting of the low-ceilinged rooms of a ship. In the middle bent milk glass plates make up a large light panel behind which the lamps are hidden, while around the edges of this panel opal glass wall brackets and small fittings built into the ceiling provide additional light.

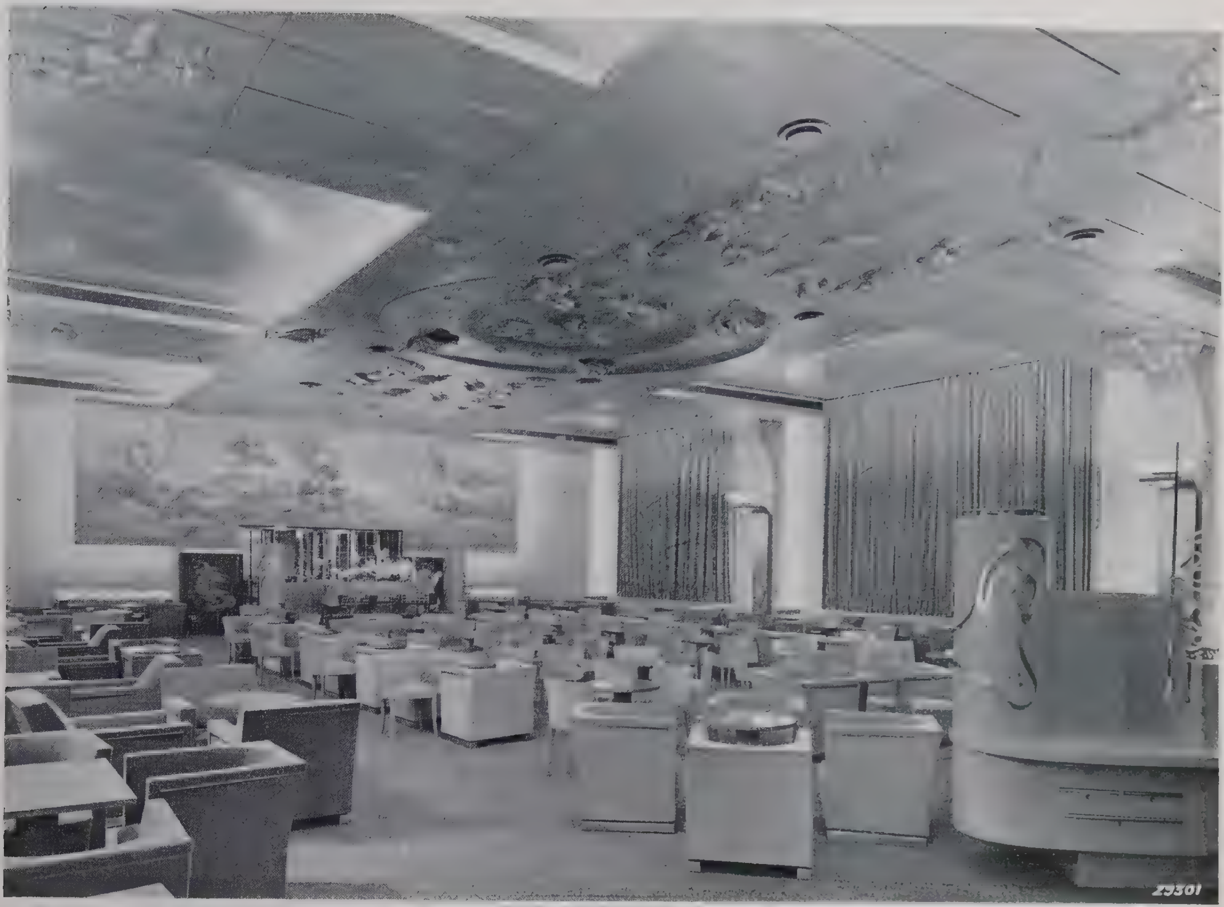


Fig. 7

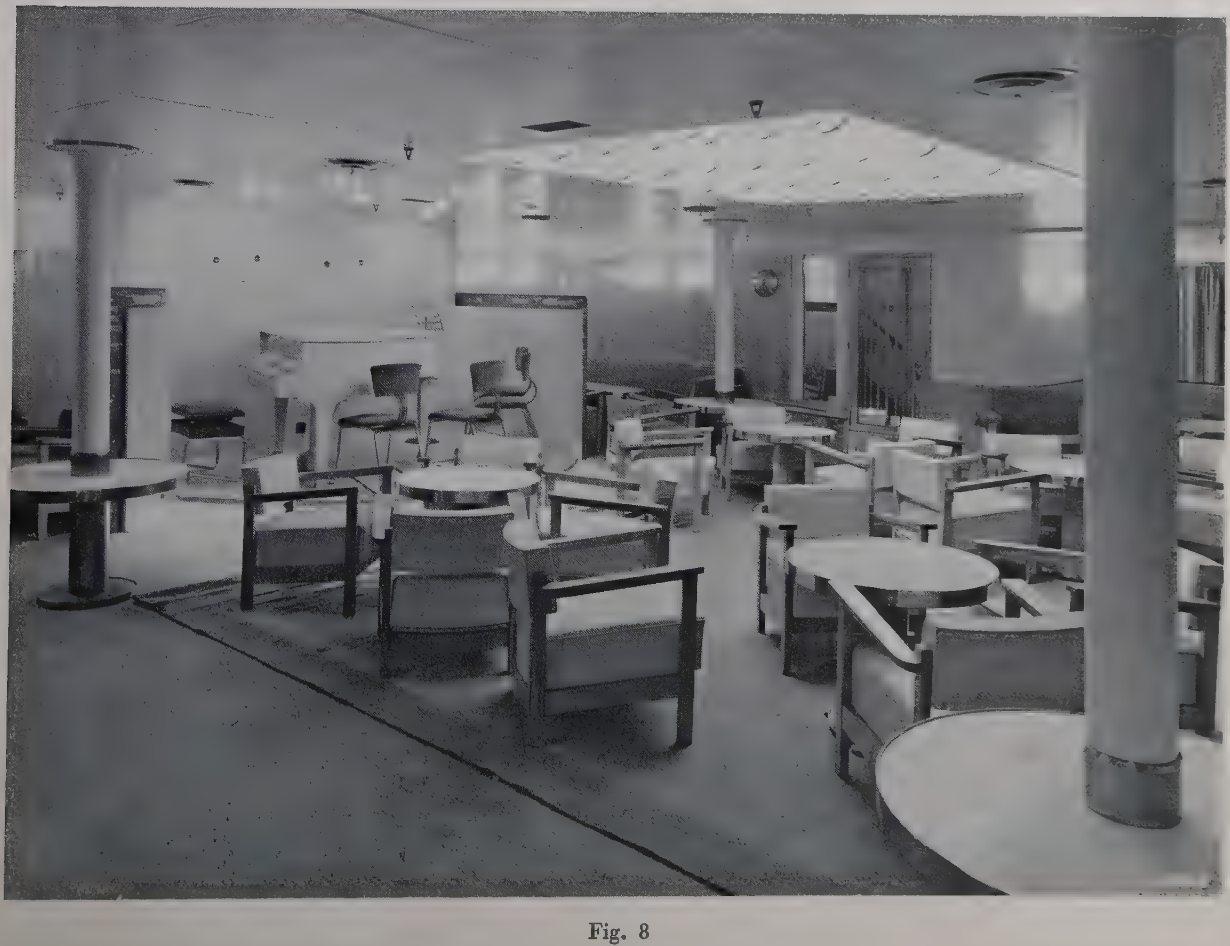


Fig. 8

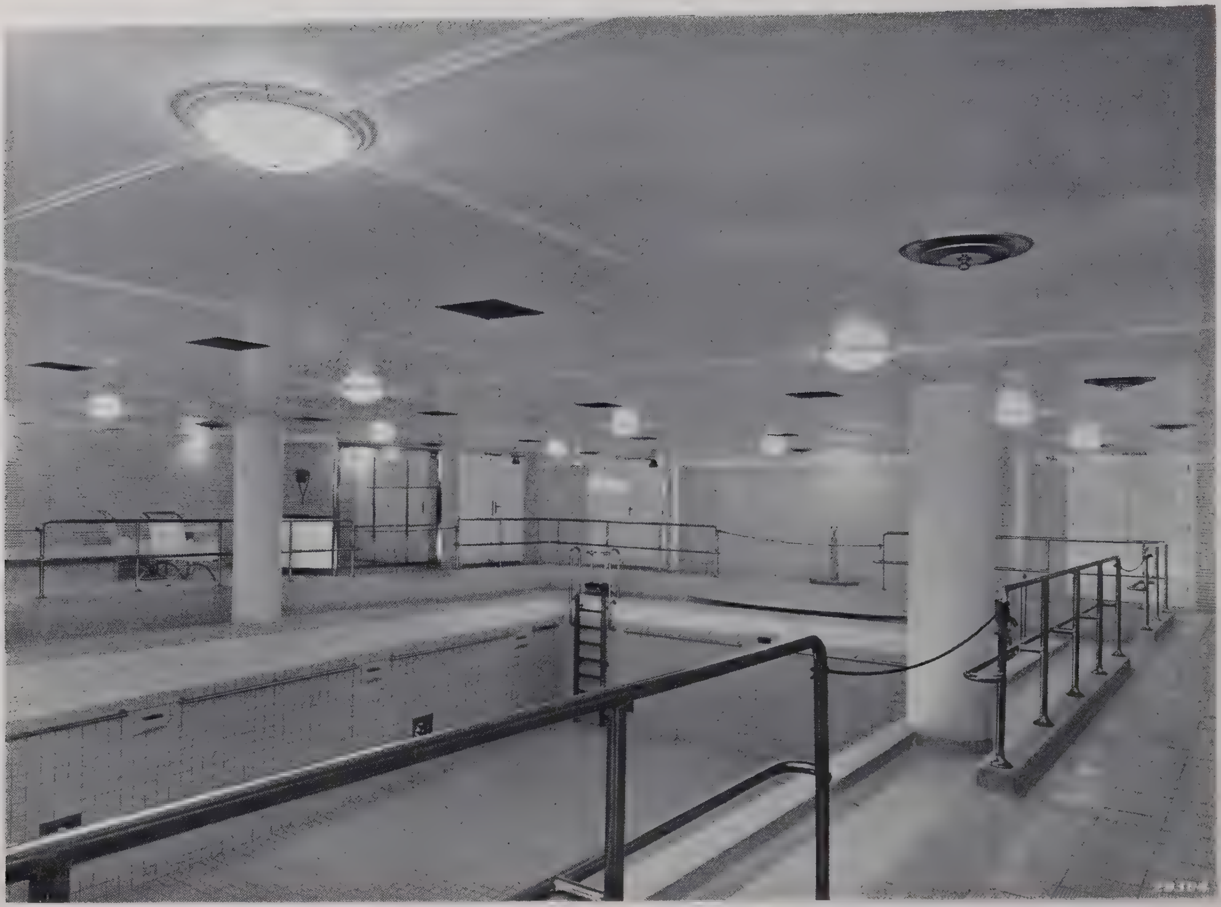


Fig. 9. The swimming pool of the "Nieuw Amsterdam" also has the low ceiling typical of ships. The plafonniers described in the text were used for the built-in illumination from above. By making the bowls of "Philiphan" glass (see Philips techn. Rev. **3**, 47, 1938) all the colours are deepened and the skin takes on a warm colour against the beautiful green of the pool.

fitted out the interiors. The text underneath the photographs gives in every case a description of the details of the lighting installation.

We should like to say a few words about the efficiency of the illumination of ships. In general it is low. Even when light colours are used, the building into the ceiling of the fittings makes the contribution of light reflected from the ceiling small, and the walls also contribute only very little because the rooms are not only low-ceilinged but have a large floor space.

For example, in the dining room of the s.s. "Ruys" of the Koninklijke Paketvaartmaatschappij, where the illumination was installed under collaboration of our consulting bureau and the technical staff of the K.P.M., an average intensity of illumination of 90 lux was measured, while the floor surface is 190 sq.m. It was found necessary to install 265 lamps of 40 W for this purpose. The 265 lamps give a light flux of $265 \times 450 = 119\,250$ lumens, of which $90 \times 190 = 17\,100$ lumens are incident on the plane where the illumination was measured. The efficiency is therefore 14.3 per cent. The efficiency may also be measured by dividing the number of lumens which falls on the plane in question ($190 \times 90 = 17\,100$) by the total number of watts ($265 \times 40 = 10\,600$). The result is 1.6 lumens per watt, while the yield of the 40 watt lamps used amounts to 11.25 lumens per watt. Compared with the results obtained in other cases these values are indeed very low.

AUDITORIUM ACOUSTICS AND SOUND ABSORPTION

by R. VERMEULEN.

534.845

The absorption of sound by the walls plays an important part in the acoustics of an auditorium. In this article the manner is discussed in which the absorption of sound takes place by thick or porous walls and panels. Further the method is indicated of obtaining the data on the absorptive capacity of different materials which are necessary for calculating the reverberation time of an auditorium. An example is finally given of the calculation of the reverberation time of an auditorium.

In order to improve the acoustics of an auditorium it seems more obvious to amplify the sound artificially [1]) than deliberately to destroy part of the sometimes small amount of sound energy. Nevertheless it will be no surprise to readers of the earlier treatises on auditorium acoustics in connection with reverberation [2]) and intelligibility [3]) that increasing the absorptive capacity of the walls is in many cases an efficient method of improving either the intelligibility of the spoken word or the quality of music. The fact that this is done at the expense of the intensity of the sound is no objection, since this can be compensated for by amplifier installations. Because of the fact that the duration of a given sound becomes shorter, speech will become more intelligible and music clearer and more brilliant. This method must not be pushed too far, since a certain degree of reverberation, especially in the case of music, is indispensable, and composers take into account, although perhaps unconsciously, a certain amount of reverberation in composing their works.

In order not to work blindly as far as acoustics are concerned in designing a concert hall or theatre, and in order not to reach a satisfactory result only after several unsuccessful and usually costly experiments with different wall coverings, it is desirable to be able to calculate the reverberation. In the well known formula of Sabine [2]) for the reverberation time [4]):

$$T = 0.16 \frac{V}{A} \quad \cdots\cdots\cdots \quad (1)$$

The value of V, the volume of the room in m^3 can always be filled in easily. The calculation of the total absorption A in m^2, however, requires more information. This total absorption is composed of the sum of the absorptions of the different wall surfaces [5]), and is expressed in "square metres of open window", in which the latter is considered to be completely absorptive [6]). The absorption A_i of each part of the walls is calculated from the surface S_i in m^2, and the absorption coefficient a_i of the material of which it is made:

$$A = \Sigma A_i = \Sigma S_i a_i \quad \cdots\cdots \quad (2)$$

Knowledge of the absorption coefficients a is the factor which makes it possible to calculate beforehand the reverberation time of a hall. Since the weakening of the sound waves takes place upon their reflection by the walls, we shall first deal generally with the mechanism of reflection of waves.

Reflection and absorption

In the air sound is propagated as a longitudinal vibration which is accompanied by a periodic change of air pressure. The momentary value of these changes we shall call the sound pressure p. For a plane wave it is proportional to the momentary value of the speed of vibration v. The quotient p/v of sound pressure and vibration speed is the so-called wave resistance W of the material [7]). The reflection and absorption of a sound wave in passing from air into another medium are determined solely by the difference in wave resistance of the two substances. The wave resistance can be represented as the product of the density ϱ and the speed of propagation c of sound:

$$W = \frac{p}{v} = \varrho c. \quad \cdots\cdots \quad (3)$$

When a plane sound wave falls perpendicularly upon the plane bounding two substances with different sound resistance, the wave cannot proceed as a whole; this follows from the transition conditions at that boundary plane. These conditions require that on both sides of the plane both the momentary value of the pressure p and that of the speed of vibration v shall be the same. If there is only one wave on both sides, then the wave resistance W, which is equal to the quotient p/v, would also have to be the same for these two waves, while the hypothesis was that the two substances have different wave resistances. The above-mentioned transition conditions for p and v can, however, be satisfied if, in addition to a direct wave proceeding through the second substance, there is also a reflected wave in the first substance which is superposed upon the incident wave.

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[1]) J. de Boer, Philips techn. Rev. **3**, 225, 1938.

[2]) A. Th. van Urk, Philips techn. Rev. **3**. 65, 1938.

[3]) R. Vermeulen, Philips techn. Rev. **3**, 143, 1938.

[4]) By reverberation time is meant the time in which the average sound level in the hall decreases 60 bB.

[5]) The absorption of the sound waves in the air itself, which may be appreciable at high frequencies, is here left out of consideration.

[6]) Absorption is also expressed in "Sabines" which units of absorption correspond with one square foot of open window = 0.093 m^2 of open window.

[7]) R. Vermeulen, Philips techn. Rev. **2**, 47, 1937.

If we indicate the quantities which relate to the incident, reflected and transmitted waves with the subscripts 0, 1 and 2 respectively, the following equations are valid:

$$p_0 = W_1 v_0;\; p_1 = -W_1 v_1;\; p_2 = W_2 v_2 \text{ and} \quad (4)$$

$$p_0 + p_1 = p_2;\; v_0 + v_1 = v_2 \quad \cdots\cdots \quad (5)$$

The pressure and the speed of the reflected and transmitted wave may easily be calculated from equations (4) and (5), as has been done in the text under *fig. 1.* For the reflection coefficient R, that is the ratio between the sound pressure of the reflected and of the incident wave one then finds:

$$R = \frac{p_1}{p_0} = \frac{-v_1}{v_0} = \frac{W_2 - W_1}{W_2 + W_1} \cdot \quad \cdots \quad (6)$$

This reflection coefficient is therefore the quotient of two amplitudes; for the absorption coefficient a, however, it is not customary to take the quotient of two amplitudes, but to define it as the ratio between the decrease in intensity of the reflected wave and the intensity of the incident wave (I_0), so that:

$$a = \frac{I_0 - I_1}{I_0} = \frac{I_2}{I_0}, \quad \text{or:} \quad a = 1 - R^2, \quad \cdot\cdot \quad (7)$$

where I_1 is the intensity of the reflected wave and I_2 that of the refracted wave. Therefore the following expression for the absorption coefficient is valid:

$$a = \frac{4\, W_1 W_2}{(W_1 + W_2)^2} \cdot \quad \cdots\cdots \quad (8)$$

In order to be able to use formulae (6) and (8) it is necessary to know the wave resistance of air and other materials. Since the density of air is 1.2 mg/cc at room temperature and the speed of propagation of sound is 340 m/sec, the wave resistance becomes

$$W_1 = 41 \text{ gr cm}^{-2} \text{ sec}^{-1} \quad \cdots\cdots \quad (9)$$

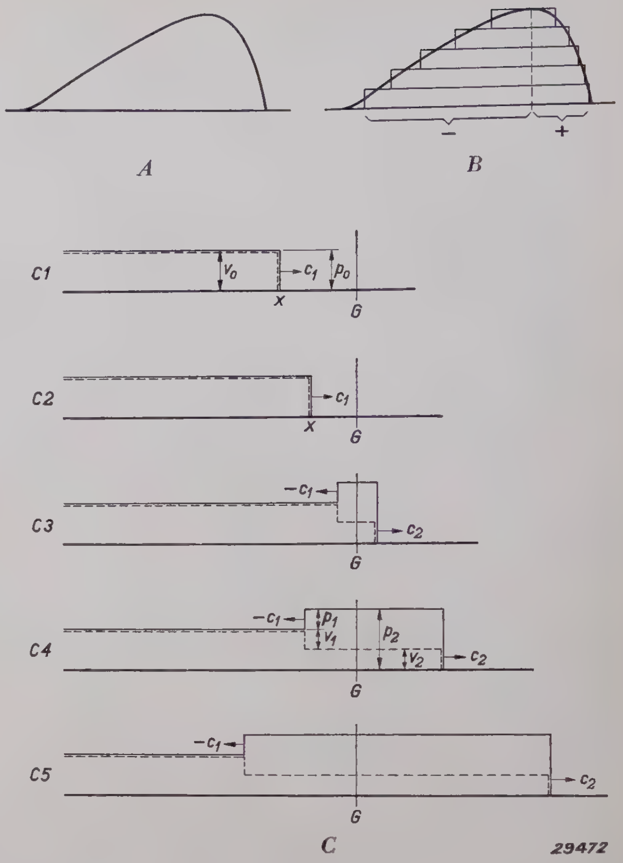

Fig. 1. Reflection of a wave impulse.

It is sufficient to discuss the reflection of a "unit impulse" (as it was called by Heaviside), because it is always possible to represent any wave (A) as made up of a large number of positive (+) and negative (—) elementary impulses (B). In such a unit impulse ($C1$) to the left of x there is a constant pressure p_0 (continuous line ———) and a velocity v_0 toward the right (broken line — — —). To the right of point x, where the wave front is situated at the moment, there is a state of rest, and the pressure is the normal atmospheric pressure. The wave front is displaced with the velocity of sound c to the right ($C2$). In the wave the ratio between the pressure p_0 and the velocity v_0, as in every plane wave, is equal to the wave resistance: $W_1 = \varrho_1 c_1 = \frac{p_0}{v_0}$, where ϱ_1 is the density. Upon reaching the boundary G ($C3$) between the two media, a wave begins in the second medium ($C4$) in which the ratio between the increase of pressure p_2 and the velocity v_2 must now be equal to the wave resistance in the second medium: $W_2 = \varrho_2 c_2 = \frac{p_2}{v_1}$. Since, however, the pressure and velocity must be continuous at the boundary plane, a wave in the reverse direction (p_1, v_1) must occur, in order that the following equations may be satisfied:

$$p_0 + p_1 = p_2, \text{ and } v_0 + v_1 = v_2,$$

with:

$$p_0 = W_1 v_0 \text{ and } p_2 = W_2 v_2$$

while in connection with the negative direction of propagation of the reflected wave: $p_1 = -W_1 v_1$. It follows from this that:

$$\frac{p_1}{p_0} = \frac{-v_1}{v_0} = \frac{W_2 - W_1}{W_2 + W_1},$$

$$\frac{p_2}{p_0} = \frac{2\,W_2}{W_2 + W_1} \text{ and}$$

$$\frac{v_2}{v_0} = \frac{2\,W_1}{W_2 + W_1}.$$

In the transition of sound from air into a wall of a given material, the phenomena which take place depend very much upon the way in which the sound is propagated in this material. As the simplest case let us suppose that the second substance is homogeneous and isotropic, and moreover that it extends infinitely on the other side of the boundary surface. This last assumption means neglecting the influence of reflection at other boundary surfaces. Since solid substances on the average certainly have a density 1000 times that of air, while in general the speed of sound through them is also greater than in air, the wave resistance W_2 will also be several thousand times that of air. It follows from formula (8) that such a wall can absorb practically no sound, and that therefore there will be practically total reflection of the sound, as may be seen clearly from formula (6). Therefore homogeneous solid substances are entirely unsuitable as absorptive material for sound.

In practice we are generally not concerned with this simple case. The wall is far from infinitely thick, and moreover sound is absorbed in the air-filled pores of many technical materials. Before going deeper into this subject we shall first extend our consideration of reflection and absorption to obliquely incident waves.

Obliquely incident waves

Although the treatment remains fundamentally the same, there is an essential difference between the reflection of normally incident waves and of obliquely incident waves, because on the one hand it is clear that in the transition conditions mutual equality of only the normal components of the vibration speed is required while, on the other hand, in the propagation of sound in the second material the wave resistance still continues to determine the ratio between the pressure and the *total* vibration speed. The formulae (4) therefore remain unaltered, but instead of formulae (5) we now obtain the following:

$$p_0 + p_1 = p_2 ; \; v_0 \cos \Theta_0 + v_1 \cos \Theta_1 = v_2 \cos \Theta_2 , \quad (10)$$

where $v \cos \Theta$ is the normal component of the speed, and the angles Θ are given in *fig. 2*. Formulae (4) for the wave resistance may be adapted in the following way for oblique incidence:

$$p_0 = W_1 v_0 = \frac{W_1}{\cos \Theta_0} \cdot v_0 \cos \Theta_0 = \frac{W_1}{\cos \Theta_0} v_{no} , \quad \text{etc.} \cdot \cdot \cdot \quad (11)$$

so that in the formulae (4) and (5) W becomes $W/\cos \Theta$ v, v_n:

$$p_0 = \frac{W_1}{\cos \Theta_0} v_{n0} ; \quad p_1 = \frac{-W_1}{\cos \Theta_1} \cdot v_{n1} ;$$

$$p_2 = \frac{W_2}{\cos \Theta_2} v_{n2} \quad \text{and} \quad \cdot \quad (4^*)$$

$$p_0 + p_1 = p_2 ; \quad v_{n0} + v_{n1} = v_{n2} \quad \cdot \cdot \cdot \cdot \cdot \cdot \quad (5^*)$$

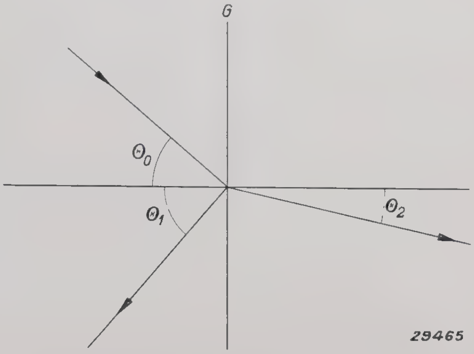

Fig. 2. Reflection and refraction at a boundary surface. Θ_0 angle of incidence, Θ_1 angle of reflection and Θ_2 angle of refraction. The relation between the angles Θ is given by Snellius' law:

$$\frac{\sin \Theta_1}{\sin \Theta_2} = \frac{c_1}{c_2} \quad \text{and} \quad \Theta_0 = \Theta_1 .$$

It may therefore be seen that the absorption depends upon the angle of incidence. Several other remarkable conclusions may be drawn from these formulae. Thus for materials for which $W_2 > W_1$ the absorption will be complete at a certain angle Θ_1, and there will therefore be no reflection, since with increasing Θ_1, $\cos \Theta_1$ decreases more rapidly than $\cos \Theta_2$, so that finally:

$$\frac{W_1}{\cos \Theta_1} = \frac{W_2}{\cos \Theta_2} \quad \cdot \cdot \cdot \cdot \cdot \quad (12)$$

For larger values of Θ_1 the reflection coefficient becomes negative, which means that due to the reflected wave the change in pressure at the wall becomes smaller than in the case of the undisturbed incident wave.

If, moreover, the speed of propagation c_2 in the second medium is greater than that (c_1) in the first, total reflection will occur with an angle of incidence greater than $\sin^{-1} c_1/c_2$, just as with light. The difference from the case of light lies in the fact that this total reflection with *light* only occurs on the transition of the wave from glass, for instance into air, while with *sound* it occurs upon transition from air into a solid substance. This is, however, not of great importance, since the reflection coefficient at solid substances, as already mentioned, usually lies close to 1.

If a sound wave moves parallel to an absorbing surface, it constitutes a limiting case for $\Theta_1 \rightarrow \pi/2$, *i.e.* $\cos\,\Theta \rightarrow 0$. According to (6) the reflection coefficient is then

$$R \rightarrow -1\,; \quad \cdot \cdot \cdot \cdot \cdot \cdot \cdot \quad (13)$$

this means that the reflected and the incident wave will just compensate each other, since at all points:

$$p_1 = -\,p_0 \text{ and } v_1 = -\,v_0 \quad \cdot \cdot \cdot \quad (14)$$

Experiments have actually shown that the primary wave disappears upon shearing incidence on a wall. In *fig. 3* the results of such experiments by von Békésy [8]) are reproduced.

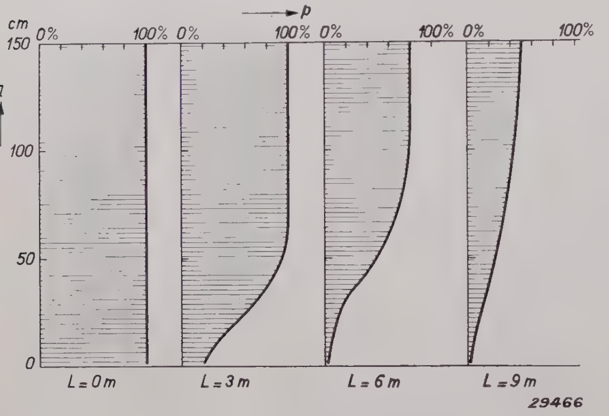

Fig. 3. A plane sound wave which proceeds parallel to a wall of absorbing material, is reduced in intensity close to the wall. The longer the distance along the wall covered by the wave, the greater the distance from the wall at which this weakening may be observed. The sound pressure p in per cent of the original value is plotted as a function of the distance l to the wall for several values of the distance L covered by the sound wave along the wall.

Porous materials

Most walls do not in the main absorb sound by being themselves set into motion under the influence of the sound vibration, but because of the fact that there are many pores in the material in which the sound wave is propagated. Because of its viscosity the motion of the air along the walls of the tiny canals is retarded, and this leads to the damping of the sound waves. In order to study the effect of this damping we begin with the equations of motion which form the basis of wave motion.

For a plane wave proceeding in the direction x through a homogeneous material without internal friction, the following differential equation is valid:

$$-\frac{\delta p}{\delta x} = +\,\varrho\,\frac{\delta v_x}{\delta t}\,, \quad \cdot \cdot \cdot \cdot \quad (15)$$

which expresses the fact that the force which acts upon unit volume is equal to the mass times the acceleration. If friction exists, a difference in pressure between front and rear sides of the element of volume will also be necessary to overcome this resistance. Let this increase be proportional to the velocity v_x. Then the differential equation becomes

$$-\frac{\delta p}{\delta x} = +\,\varrho\,\frac{\delta v_x}{\delta t} + r\,v_x\,, \quad \cdot \cdot \quad (16)$$

in which the factor r may be called the specific resistance. With sinusoidal vibrations with a frequency $\omega/2\pi$ the above may be written in the following form:

$$-\frac{\delta p}{\delta x} = (j\omega\varrho + r)\,v_x = j\omega\varrho\left(1 - j\,\frac{r}{\omega\varrho}\right)v_x =$$

$$= \varrho\,(1 - j/\nu)\,\frac{\delta v_x}{\delta t}\,, \quad \cdot \cdot \quad (17)$$

in which thus a "reduced frequency"

$$\nu = \omega\,\varrho/r \quad \cdot \cdot \cdot \cdot \cdot \cdot \cdot \quad (18)$$

has been introduced. By comparing formulae (15) and (17) with each other it may be seen that it is only necessary to substitute $\varrho\,(1 - j/\nu)$ for ϱ in the previous formulae. Since the velocity of sound is inversely proportional to the square root of the density, it is changed to $c = c_0/\sqrt{1 - j/\nu}$. In this complex speed of propagation the fact is expressed that the waves during propagation also diminish in amplitude. Therefore for the behaviour of the sound wave in the canals of the second medium there is a separate wave resistance:

$$W_2' = \varrho_0\,(1 - j/\nu)\cdot\frac{c_0}{\sqrt{1 - j/\nu}} = \varrho_0\,c_0\,\sqrt{1 - j/\nu}. \quad (19)$$

Since, however, only a part σ of a cross section parallel to the boundary plane is occupied by the air canals, and the part $1-\sigma$ allows of no air displacement, the wave resistance W_2 of the canals toward the outside appears to be $1/\sigma$ times as great

$$W_2 = \frac{W_2'}{\sigma} = \frac{\varrho_0 c_0}{\sigma}\,\sqrt{1 - j/\nu}. \quad \cdot \cdot \quad (20)$$

By means of this value W_2 of the wave resistance the absorption can be calculated of a layer of porous material placed in front of a heavy wall. The result will depend upon the thickness d of the layer, the specific resistance r and the frequency $\omega/2\pi$. It will then be found that it is possible [9]) to express the absorption coefficient a in two dimensionless combinations of these quantities, namely the "reduced frequency" ν already introduced and the "reduced resistance":

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[8]) G. von Békésy, Z. techn. Phys. **14**, 6, 1938.

[9]) L. Cremer, Elektr. Nachr. Techn. **10**, 242, 1933; **12**, 338 and 366, 1935.

$$\delta = \frac{dr}{\varrho_0 c_0} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

The value *dr* is the direct current resistance of a layer with the thickness *d*, which could therefore be measured, if necessary, by determining the current of air which flows between front and rear sides under the influence of a small difference in pressure.

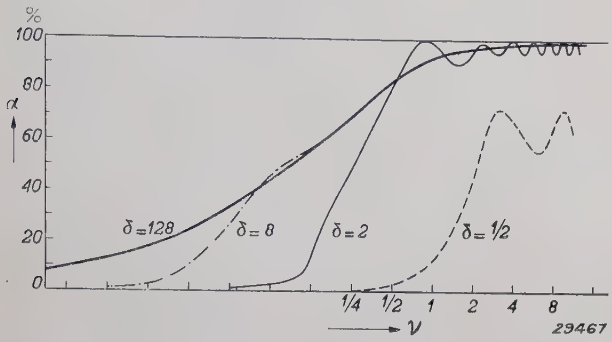

Fig. 4. The absorption coefficient α of the porous material placed in front of a hard wall is given above as a function of the "reduced frequency" $\nu = \omega\varrho/r$ with the reduced quantity $\delta = \frac{dr}{\varrho c}$ as parameter. When the reduced direct current resistance of the wall is large ($\delta = 128$), (*i.e.* when it is very thick or has a high specific resistance, and thus small pores) the absorption at low frequencies (*i.e.* at wave lengths longer than the thickness of the wall, thus $\nu < {}^1/_{20}$) is small, and increases regularly with increasing frequency, until at higher frequencies ($\nu > 4$) the absorption is practically complete. At smaller values ($128 > \delta > 1$) of the reduced resistance, the behaviour is practically the same for frequencies which have a wave length smaller than 6 times the thickness of the wall, but the absorption decreases rapidly toward lower frequencies. For very small values of the reduced resistance ($\delta < 1$) complete absorption is never attained. The reflection at the hard wall becomes increasingly less disturbed; the absorption does, however, change for different frequencies due to the occurrence of stationary vibrations in the material.

In *fig. 4* the absorption coefficient α is plotted as a function of ν for different values of δ as a parameter. It may be seen from this figure that the absorption decreases sharply for low frequencies, which is quite understandable when it is kept in mind that nodes of the air vibrations are formed at the walls, so that the velocity of the air can only reach a significant value at a distance from the wall of the order of $\lambda/2\pi$. If the wall is much thinner than $\lambda/2\pi$, it may not be expected that much energy will be dissipated by friction in the air motion in the pores.

When it is understood that one of the conditions to be observed in order to obtain a high absorption coefficient is the avoidance of reflection at the front surface, a material will be sought which is composed of several layers in such a way that the wave resistance of the first layer differs only slightly from that of air, and that of the following layers becomes successively greater in order to provide adequate adsorption of the wave. With a medium thickness of the wall covering, however, this method does not provide such a great improvement that it would make up for the complications.

Moving panels

Not only the presence of pores in a wall, as discussed above, can serve to make a wall more suitable for the absorption of sound. It is known that halls with a wall covering of wood often possess good acoustic properties. The thickness of such wooden panels is always so small compared with the wave length of audible sound that the mutual differences of phase of the movements in the wall are extremely slight and there can scarcely be any question of wave propagation *in* the panel. The behaviour of such a thin wall is now characterized, not by a wave resistance, but by its impedance to motion Z_2, which gives the ratio between the force F acting on the wall and the velocity v which it obtains as a consequence:

$$Z_2 = \frac{F}{v} = \frac{p}{v} S, \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

where S represents the area of the thin wall considered. From equation (22) it may be seen that the impedance to motion per unit area, Z_2/S now takes the place of the wave resistance $W = p/v$ in the case of the infinitely thick wall, so that for the reflection coefficient with normal incidence the following equation takes the place of equation (6):

$$R = \frac{p_1}{p_0} = \frac{-v_1}{v_0} = \frac{Z_2/S - W_1}{Z_2/S + W_1} . \quad . \quad . \quad (23)$$

If the panel is fastened rigidly against a heavy wall, the impedance of the wall will thereby be made large. When it is fastened on laths with an air space between panel and wall it is much more mobile. The cushion of air will act as an elastic spring and will increase the resonance frequency of the wall to such an extent that in calculating its value a satisfactory approximation is obtained by considering the panel itself as absolutely flexible and considering only the stiffness of the air cushion and the mass of the panel.

Beginning with the law for adiabatic change of state of a gas, $pV^{\varkappa}$ = constant, one obtains upon differentiation:

$$\frac{\Delta p}{p} + \varkappa \frac{\Delta V}{V} = 0 \quad . \quad . \quad . \quad . \quad . \quad (24)$$

The mechanical stiffness of a cushion of air with a surface S and a thickness d is defined as the ratio of the force ΔK on the surface to the decrease in thickness caused by that force $-\Delta d$.

$$-\frac{\Delta K}{\Delta d} = -\frac{S\Delta p}{\Delta V/S} = -\frac{\Delta p}{\Delta V}\cdot S^2 \cdot \cdot \quad (25)$$

The stiffness per unit of surface is therefore

$$-\frac{\Delta p}{\Delta V}\cdot S = +\frac{\varkappa p}{V}\,S = +\frac{\varkappa p}{d} = \frac{\varrho c^2}{d}, \quad (26)$$

since the velocity of sound is given by $c = \sqrt{\varkappa p/\varrho}$. For a mass m per unit of surface of the panel the following value is found for the resonance frequency f:

$$2\pi f = \omega = \sqrt{\frac{\varrho c^2}{dm}} \quad \cdot \cdot \cdot \cdot \cdot \quad (27)$$

In the neighbourhood of this frequency the impedance Z_2 of the wall can be much smaller than would be the case without the air cushion. It thereby becomes possible for the values of Z_2/S and W_1 (the wave resistance of air) to approach each other more closely in formula (23), and in this way the condition for a smaller coefficient of reflection is more nearly satisfied. Energy is then taken up by the panel from the incident waves, and it will depend upon the damping what part of this energy is destroyed and what part will be radiated again later as sound energy. It appears that under certain circumstances this latter radiation may lead to disturbing increase of the reverberation time with a certain frequency, but the absorption will usually be high due to a sufficiently rapid damping, and the reverberation will be shortened exactly at the resonance frequency. Experiments by Erwin Meyer [10]) have shown that the above considerations are somewhat too simple.

It is indeed true that the thickness of the cushion of air is usually so small compared with the wave length, that it may actually be considered as a simple spring within a wide frequency range, but that the other dimensions of the cushion of air are often such that stationary vibrations are very well possible, which not only make the theory incalculable, but which also decrease the absorption very much. If these vibrations are prevented (by dividing the air space into sections with partitions), or damped (by filling) a better agreement with the measurements is found (*fig.* 5). For damping it is not necessary to fill the air space completely with a porous material (fig. 5*b*); it is already enough for example if a 5 cm thick wadding is introduced around the edges (fig. 5*c*).

By making a certain number of perforations in the panel and filling the air space with porous material, a gradual transition can be obtained from the properties of a moving panel to those of a porous material. The holes for this purpose need not be large: if 4 per cent of the surface consists of holes, the effect is appreciable, with 15 per cent the action is almost the same as that of a porous material alone.

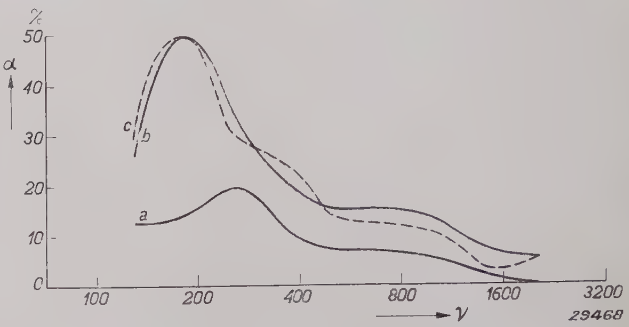

Fig. 5. Absorption coefficient a per m^2 expressed in per cent as a function of the frequency in c/s for 5 mm thick triplex panels of 1.5 m by 1 m, placed 5 cm in front of the wall.
a) undamped cushion of air.
b) air space filled with a thickness of 4 cm of wadding.
c) only the edges of the air space sealed with 5 cm of wadding.

The great importance of these resonating panels is, that a high absorption coefficient can be obtained in the low-frequency range where the porous substances were found not to give satisfactory results. At the same time there is the possibility of fixing the maximum absorption at a desired frequency by the choice of the thickness of the cushion of air. It will be found stated [11]) that in halls with a calculated short reverberation the acoustics are improved by wooden resonating panels. This experience should probably be interpreted to mean that the curve of the reverberation as a function of the frequency is made flatter in this way.

Measurement of absorption

While it is true that the above considerations give some idea of the way in which sound absorbing materials act, it is, however, very desirable to measure the absorption directly on a sample of the material. It would for example be possible to determine the reflection coefficient at different angles of incidence, and to calculate from the results the average value of the absorption coefficients over the different directions according to the formula:

$$a_r = 2\int_0^{\pi/2} a(\Theta)\,\sin\Theta\,\cos\Theta\,d\Theta, \quad (28)$$

in which a value is ascribed to the different absorption coefficients which is proportional to the solid angle for which they are valid. It is, however, still an open question whether this formula gives the value of the absorption coefficient which must be used in Sabine's formula for calculating the reverberation time. It seems therefore preferable to determine the absorption coefficient by measuring with relatively small samples of material the difference in the reverberation time of a test chamber in which the material is used and that in the same chamber when the material is not used.

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[10]) E. Meyer, Elektr. Nachr. Techn. **13**, 98, 1936.

[11]) H. Baginall and A. Wood, Planning for good acoustics, p. 137, Methuen & Co. Ltd.

If the volume of the test chamber is V, the area of the test material S_2 and the reverberation time without and with the material T_1 and T_2 respectively, formulae (1) and (2) give for the absorption coefficient:

$$a = 0.16\,\frac{V}{S_2}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \cdot \cdot \cdot \cdot \quad (29)$$

In order to use as little as possible of the test material and yet to have as accurate as possible measurements of the absorption coefficient, the characteristic absorption of the chamber itself upon which that of the test material is superposed should be kept as small as possible. The test chambers for these absorption measurements must therefore be so-called "hard" chambers (Hallräume, reverberation chamber). In such chambers, however, the deviations from Sabine's law make themselves felt, and the measured absorption coefficient is found not to be independent of

1) the position of the sample in the room,
2) the size of the sample,
3) the absorption of the rest of the wall space,
4) the size of the reverberation chamber.

It may be stated in general that too small samples give too high an absorption coefficient, and that the other influences are especially noticeable with materials having large absorption coefficients. The fact that this makes it difficult to compare the results obtained in different laboratories, may be seen from the comparison of measurements made in different countries [12]). Values of the absorption coefficient were measured with the same material at 265 c/s, for example, and the results varied from 0.33 to 0.58, while at 512 c/s they varied from 0.69 to 0.99. In *fig. 6* the influence of the size of the sample on the absorption coefficient is shown. Although it may be seen from the figure that with sufficiently large dimensions of the sample a practically constant absorption coefficient is obtained, even this final value is not always the same for two different laboratories.

An extraordinary result may be mentioned which was obtained in an unusually large reverberation test chamber with 1 m^2 of slag-wool at 2900 cycles per sec. A "record" value of 300 per cent was obtained for the absorption coefficient calculated according to formula (7). These deviations must not be taken too tragically since they occur chiefly under extreme conditions, and under more ordinary conditions and with reasonable application satisfactory results may be obtained. In order to give an idea of values found, several values of the absorption by different material as found in the literature are given in *table I*.

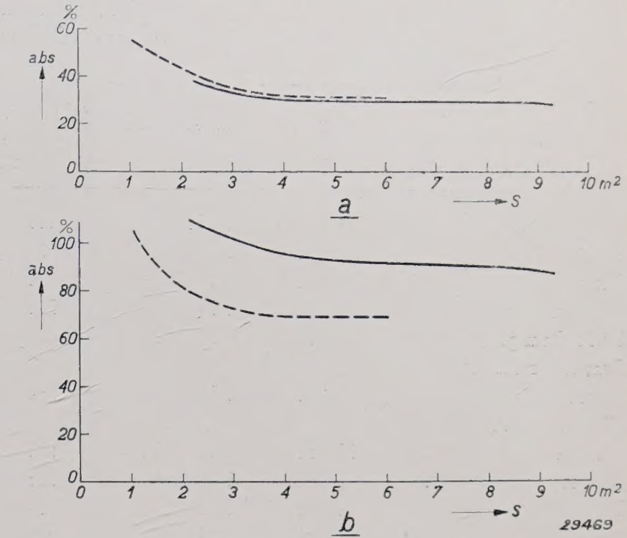

Fig. 6. Absorption coefficient as a function of the surface area of the absorbent material at 256 cycles/sec (*a*) and at 512 c/s (*b*), measured in two different American laboratories. Curves of same laboratory continuous and broken lines respectively.

Table I

Absorption with 512 c/s.

Open window	100%
Opening of stage	25 ÷ 40%
Curtains	15 ÷ 50%
Rug	20 ÷ 40%
Slag-wool	60—80%
Felt	50—80%
Acoustic plaster	38—70%
Brick wall	3%
Wood	6—10%
Area occupied by public	96%
Per person	0,5 m^2 open window
Per unoccupied chair (upholstered)	0,3 m^2 ,, ,,
Per unoccupied chair (not upholstered)	0,03 m^2 ,, ,,

The most important contribution to the total absorption of a room is not only difficult to measure, but is also variable, since it is provided by the

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[12]) R. M. Morris, G. M. Nixon and J. S. Parkinson, J. acoust. Soc. Amer. **9**, 237, 1938 and E. Meyer, Akust. ZS. **2**, 180, 1938.

Table II

Calculation of the reverberation time of Queen's Hall, London.

Volume of the hall: 422 000 cubic feet.
Number of seats : 2 026
Volume per seat : 208 cubic feet.

Material	Surface in sq.ft.	Absorption coefficient	Absorption in sq.ft. open window
Hard plaster	19 400	0.025	485
Glass	1 000	0.027	34
Vents	180	0.5	90
Wooden panels	5 080	0.1	508
Dado linings	1 500	0.1	150
Painted cloth on wood	1 200	0.12	144
Wooden floor and stage	11 250	0.06 (0.10)	608
Carpet	4 790	0.2 (0.10)	863
Linoleum	3 280	0.03	89
Organ-case	1 000	0.08	80
Upholstered chairs	2 026 in number	1.3 sq.ft. per chair	2 633

Type of occupation	Number of persons	Absorption in sq.ft. per person	Absorption in sq.ft. open window
Orchestra	90	4,7	423
Choir	250	4,7	1 175
Audience (full)	2 026	4,7—1,3	6 888
Audience ($^1/_3$)	675	4,7—1,3	2 295

Type of occupation	Total absorbing surface in sq.ft.	Reverberation time in sec.
Empty hall	5 660	3.6
Choir + orchestra	7 166	2.9
$^1/_3$ audience + choir + orchestra	9 533	2.2
Audience + choir + orchestra	14 160	1.4

audience. The previously mentioned method[13]) makes it possible to determine the absorption coefficient during a concert without interruption (even at different frequencies), by using filters. Here also it is found difficult to speak of a single definite absorption coefficient or of an absorption in sq.ft. of open window per person: a completely filled hall has a considerably lower absorption per person than a half-filled one (*fig. 7*). On the other hand it is fortunate that this is so, because in this way the reverberation time will vary less with changing degree of occupation. In order to avoid large differences it is a good thing to use heavily upholstered chairs which make up for the absorption of the missing audience.

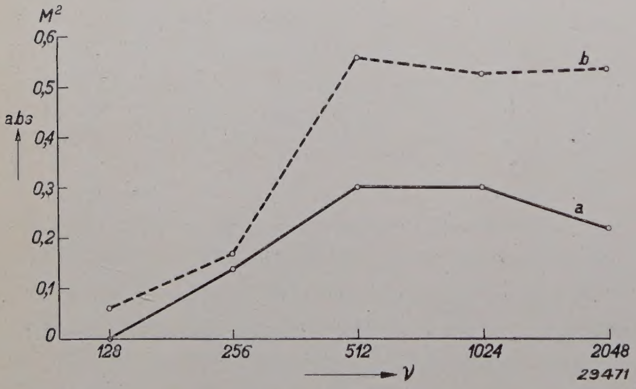

Fig. 7. The variation of the absorption per person in a hall as a function of the frequency ν.
a) hall completely occupied
b) hall half occupied.

Calculation of the reverberation time

In *table II*[14]) an example is given of the calculation of the reverberation time of an auditorium,

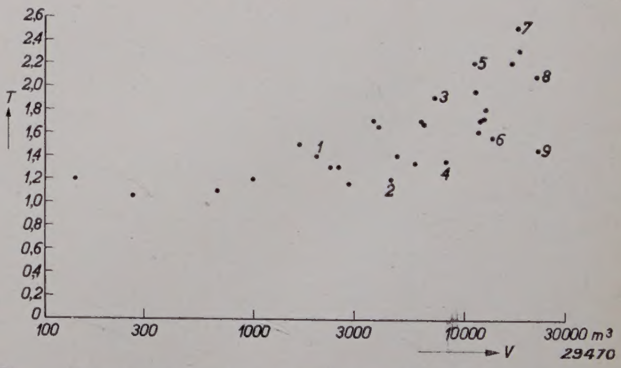

Fig. 8. Reverberation time T as a function of the volume V of several auditoria known to have good acoustics, *inter alia* the following:
1) Altes Gewandhaus, Leipzig.
2) Examination Hall, Cambridge. (Eng.).
3) St. Margaret's, Westminster.
4) Musikvereinsaal, Vienna.
5) Wagner Theater, Bayreuth.
6) Grand Theatre, Moscow.
7) Thomas Kirche, Leipzig.
8) Eastman Theatre, Rochester (U.S.A.).
9) Salle Pleyel (new), Paris.
This figure shows clearly that the longest reverberation time occurs in churches and the shortest in theaters, while concert halls usually lie in the middle.

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[13]) E. Meyer and V. Jordan, Elektr. Nachr. Techn. **12**, 213, 1935; *cf.* also: Philips techn. Rev. **2**, 266, 1937.

[14]) H. Baginall and A. Wood, Planning for good acoustics, p. 109 - 112.

Queen's Hall in London. The surface area of the different materials is calculated, and the absorption coefficient is estimated. In the case of the chairs the absorption per chair is used. In several cases 10 per cent is deducted because the surfaces in question are not entirely freely exposed to the sound. In the second half the absorption is calculated separately for the various groups of people present in the hall. The absorption of the occupied chairs is of course deducted.

It is now possible to calculate the total absorption and thus the reverberation time, according to Sabine for different combinations as done in the third part of the table. It may be seen that the audience has a very great influence. In calculating the absorption of a hall it is certainly desirable to find out whether or not the reverberation time becomes too long when the hall is only partially occupied. There must be sufficient permanent absorption in the hall in the form of upholstered seats or on the walls. Then in order not to have too short a reverberation time when the hall is fully occupied, the volume of the room must not be too small.

Fig. 8 gives an idea of the reverberation times usual in practical cases. The reverberation time T is represented as a function of the volume V of the hall for various halls known to possess good acoustics.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS OF THE N.V. PHILIPS' GLOEILAMPENFABRIEKEN

1319: W. de Groot and F. M. Penning: Die Ergiebigkeit der Neutronenproduktion durch D-Kanalstrahlen (Physica **5**, 512 - 520, June 1938).

From the yield of neutrons produced by deuterium ions upon striking plates of deuterium phosphate, lithium, beryllium and carbon as measured by Amaldi, Hafstad and Tuve, the effective diameters of these atomic nuclei were determined as functions of the speed of the projectile, use being made of the values found by Mano of the range in air of charged particles and of the atomic stopping power of these elements. With the help of the approximation formulae following from these values, it is possible to extrapolate the yields as found by Amaldi, Hafstad and Tuve for lower energies also. The results of Ladenburg and others, Scherrer, Kallmann and other authors can be made to agree with these formulae by a suitable choice of parameters. It is found necessary in some cases to determine once more the recalculation factor for the transition from a compound to pure deuterium, making use of the proportionality of the atomic stopping power to the square root of the nuclear charge number.

1320: J. H. de Boer: Interpretation of molecular phenomena by means of potential curves. IV. Fluorescence and phosphorescence; Activation energy (Ned. T. Natuurk. **5**, 57 - 64, Mar. 1938).

The significance of the Franck and Condon principle is discussed in relation to the position of absorption and emission bands of fluorescent substances. The chemical activation energy can be deduced from the potential curves. Activated adsorption and explosive substances are finally dealt with briefly.

1321: J. H. de Boer: Interpretation of molecular phenomena by means of potential curves. V. Colloids (Ned. T. Natuurk. **5**, 65 - 69, Apr. 1938).

Colloidal phenomena are discussed from the standpoint of potential curves according to the considerations of Hamaker (*cf* **1286**).

1322: C. J. Bakker, W. de Groot and F. M. Penning: Neutron-producing nuclear reactions and their yields (Ned. T. Natuurk. **5**, 102 - 115, May 1938).

A critical survey is given of the present insight into the production of neutrons by various nuclear reactions. The results obtained by others are compared with those of several measurements by the authors, and a satisfactory agreement is found. Special mention must be made of the fact that Penning was able to produce neutrons in a closed tube filled with deuterium at a low pressure with a discharge in a magnetic field in which the electrons must move in spiral paths between the electrodes. Deuterium molecular ions were formed, which, after being accelerated, struck a plate covered with a compound of zirconium and deuterium, thereby producing neutrons.

1323: J. de Boer: Sensitivity at different frequencies of a spherical model of a pressure gradient microphone (Physica **5**, 542 - 552, July 1938).

The sensitivity was calculated of a spherical model of a pressure gradient microphone as a function of the frequency of the sound wave of the radius of the sphere. For wave lengths greater than 2π times the radius of the sphere the sensitivity is found to be independent of the frequency. The calculated results agree with the results of measurements.

1324: M. J. Druyvesteyn: The interaction between an electron beam and a plasma (Physica **5**, 561 - 567, July 1938).

The way in which a beam of electrons is retarded and scattered in direction and energy by a plasma is calculated. Since the interaction takes place according to the Coulomb law, an upper limit must be determined for the distance at which an electron of the beam is still affected by the electrons and ions of the plasma.

1325: W. Elenbaas: Der Einfluß der positiven Ionen auf die Beweglichkeit der Elektronen im Quecksilberbogen (Physica **5**, 568 - 580, July 1938).

The electrical field strength in a high pressure mercury discharge is measured at pressures lower than those ordinarily used, and in tubes with diameters of 11, 19 and 37 mm. In this pressure range differences are found between the measurements and the calculations made on the basis of measurements in the normal pressure range. It is found that the deviations may be accounted for by considering the influence of the positive ions on the mobility of the electrons as calculated by Gvosdover.

1326: C. J. Bakker: Current distribution fluctuations in multi-electrode radio valves (Physica **5**, 581 - 592, July 1938).

The fluctuations are discussed which occur in the current in a radio valve due to the distribution of the current over the different electrodes. Formulae are derived for the fluctuations in the anode current of a pentode. Experiments carried out on pentodes agree satisfactorily with the theoretical expressions.

1327: J. A. M. van Liempt: Der Reflexionskoeffizient einiger organischen Stoffe (Rec. Trav. chim. Pays Bas **57**, 694 - 696, June 1938).

From the Raman frequency of an organic molecule and the variation of its sublimation pressure the reflection coefficient of the organic substance in question can be calculated by means of the formula (*cf.* **1051**) for the sublimation pressure. For the reflexion coefficients of benzene, p-dibrombenzene and naphtalene, values from 0.99 to 1 are found in this way.

1328: J. D. Fast Außerordentlich grosse Löslichkeit von Stickstoff und Sauerstoff in einigen Metallen; studiert an Zirkon und Titan (Metallwirtschaft, **17**, 641 - 644, June 1938).

Titanium and zirconium have an abnormally large capacity for dissolving nitrogen and oxygen. One result of this fact is that these gases have a very unfavourable influence on the mechanical properties of these metals. In the case of thorium, nitrides and oxides are formed which do not dissolve in the metal, and which are therefore much less harmful. It follows from X-ray examination that at the most, 40 atom per cent of oxygen and 20 of nitrogen dissolve in zirconium. The transition point (865 ± 10° C) from hexagonal (α) to cubic (β) zirconium changes, due to the solution of oxygen or nitrogen, into a transition range, the width of which depends upon the amount of gas dissolved; with 10 atom per cent of oxygen it is more than 600°. Since the specific weight of a rod of zirconium rises from 6.54 to 6.60 upon taking up 10 atom per cent of oxygen, it may be concluded that the oxygen atoms are taken up in the open spaces of the metal lattice. In contrast to the case with hydrogen, the oxygen and nitrogen taken up by zirconium and titanium cannot be driven out by heating in a high vacuum.

1329: W. G. Burgers: Elektronenoptische Beobachtungen der Zwillingsbildung in Nickeleisen (Metallwirtschaft **17**, 648 - 650, June 1938).

The concept proposed by Carpenter and Tamura, that recrystallization twins are due to defective crystal growth, and need not necessarily develop, for example by starting from preformed twin crystals along slip places, is confirmed in experiments carried out with the aid of the electron microscope on crystals of nickel-iron which exhibit twin structure. This of course does not prove at all that the concept must be generally valid.